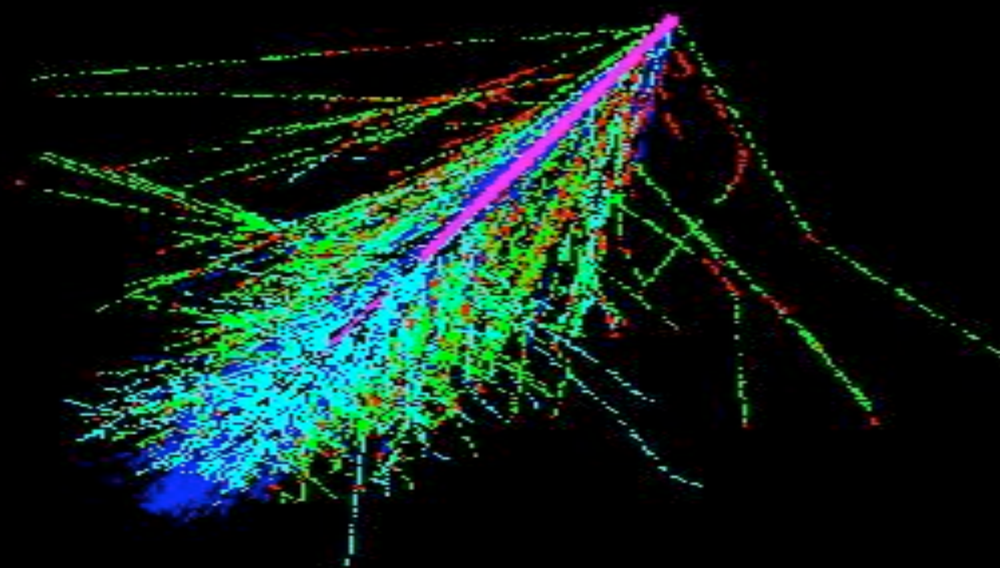
PANIC 05

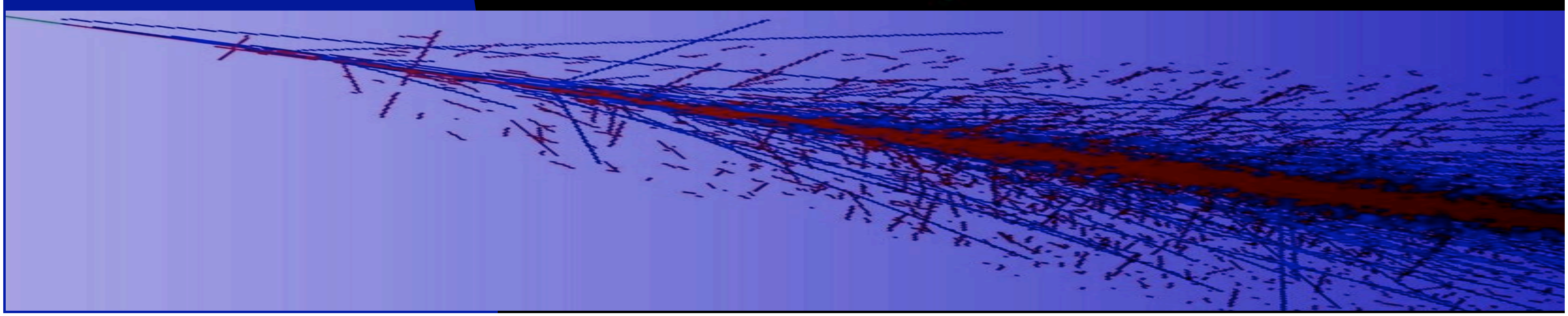
New Cosmic Rays at the Highest Energies



Angela V. Olinto

A&A, KICP, EFI

The University of Chicago



Outline

Background

Expectations

Old Data

New Data

&

Outlook

Cosmic Rays Observables

SPECTRUM

COMPOSITION

ANISOTROPIES in Sky

MULTIPARTICLE INFO:
- TeV gamma rays
- Neutrinos

Cosmic Rays Observables

SPECTRUM

COMPOSITION

ANISOTROPIES in Sky

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Cosmic Rays

1912 discovered by Victor Hess

Energy range:

~ 10^9 eV to > 10^{20} eV

1938 Pierre Auger discovered

Extensive Air Showers (EAS)

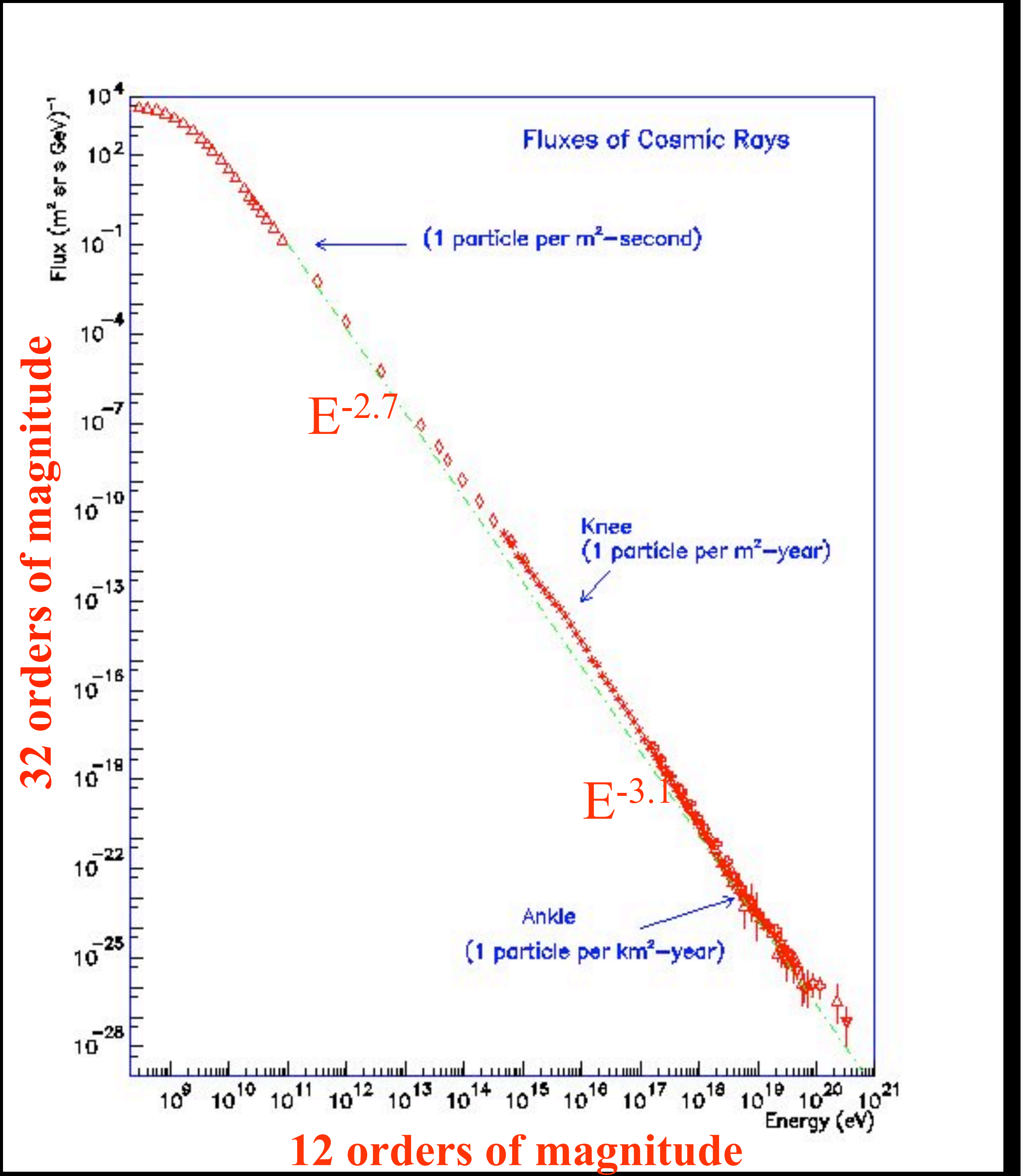
ORIGIN?

Unknown!

soon to be a

Century Old Puzzle!

at all energies…



Cosmic Rays Observables

SPECTRUM

COMPOSITION

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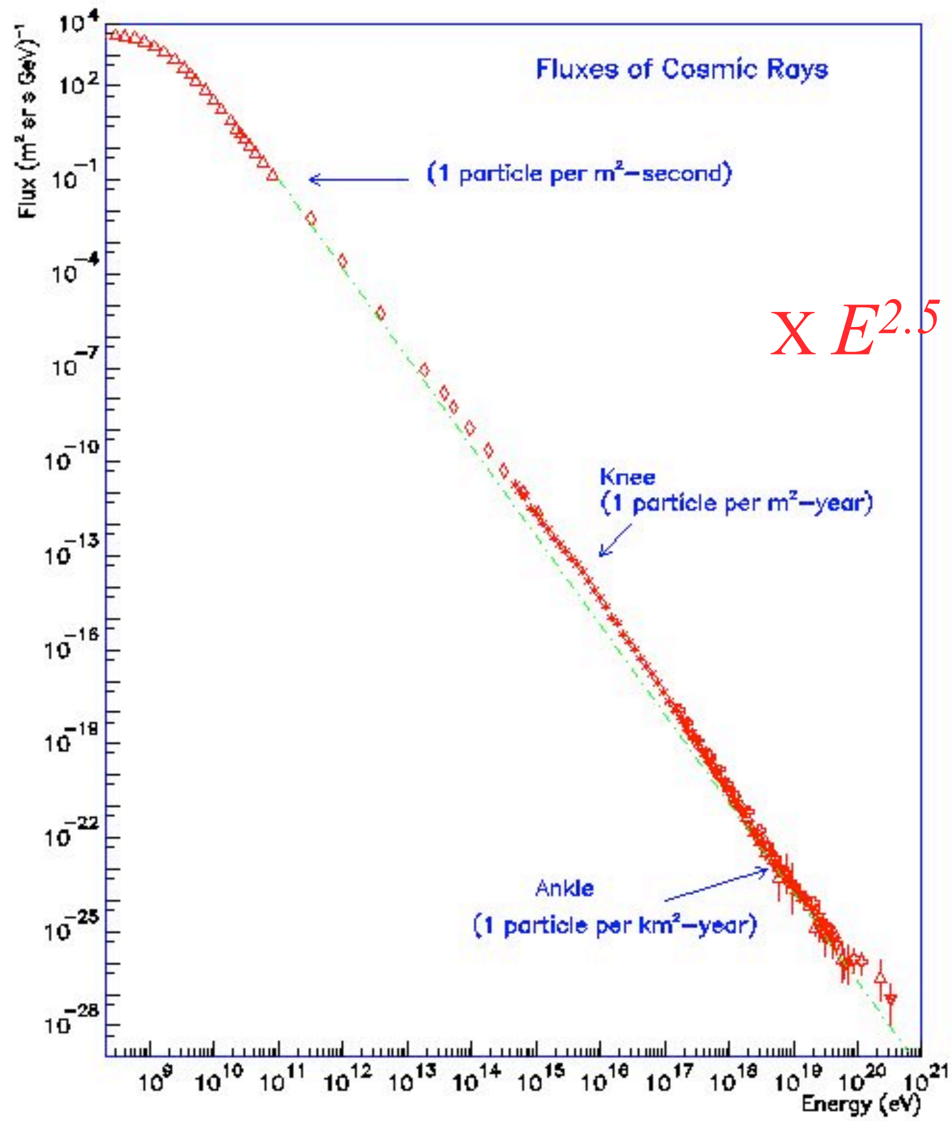
- Neutrinos

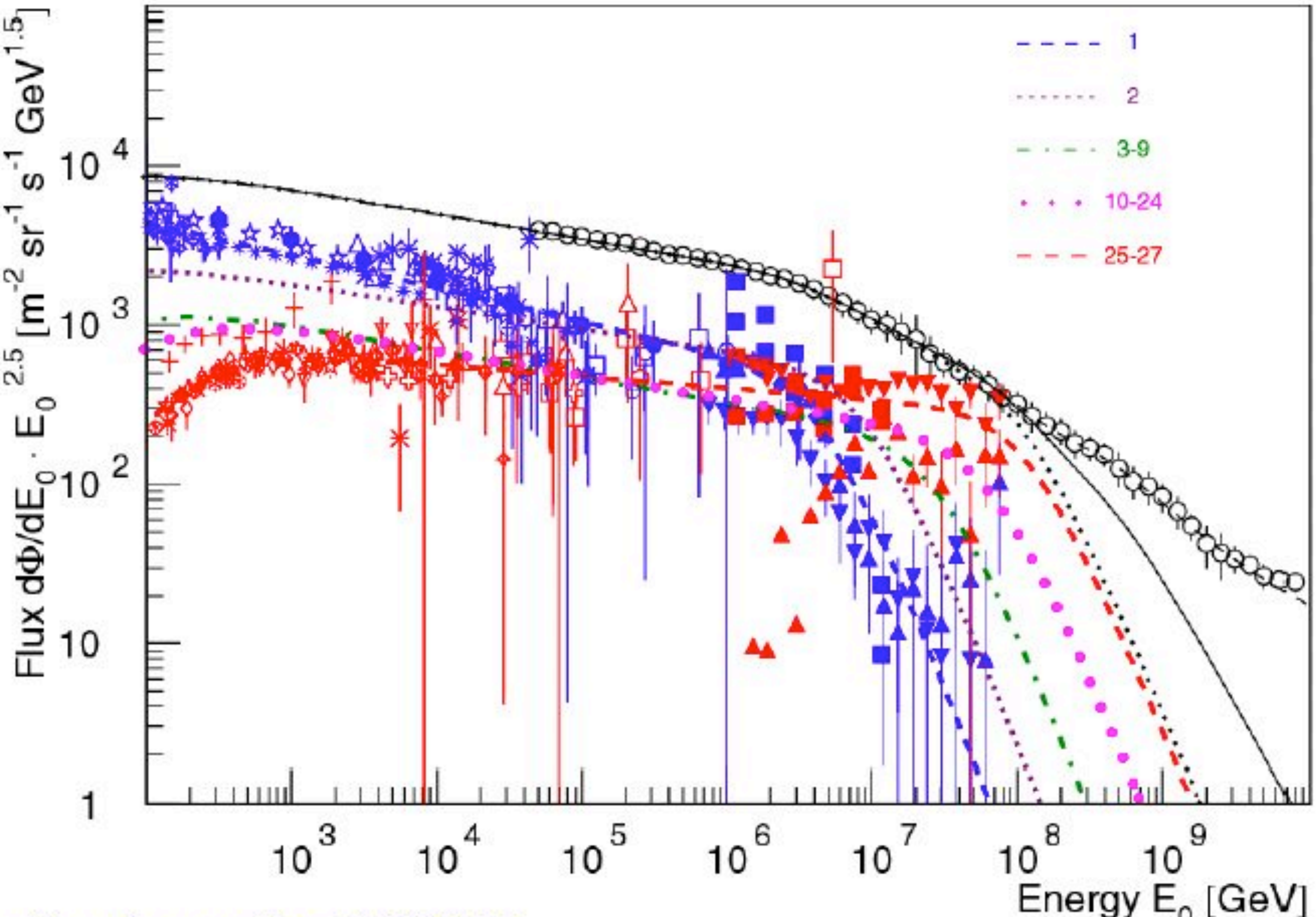
Cosmic Ray Spectrum

$dN/dE \sim E^{-2.7}$ to E^{-3}



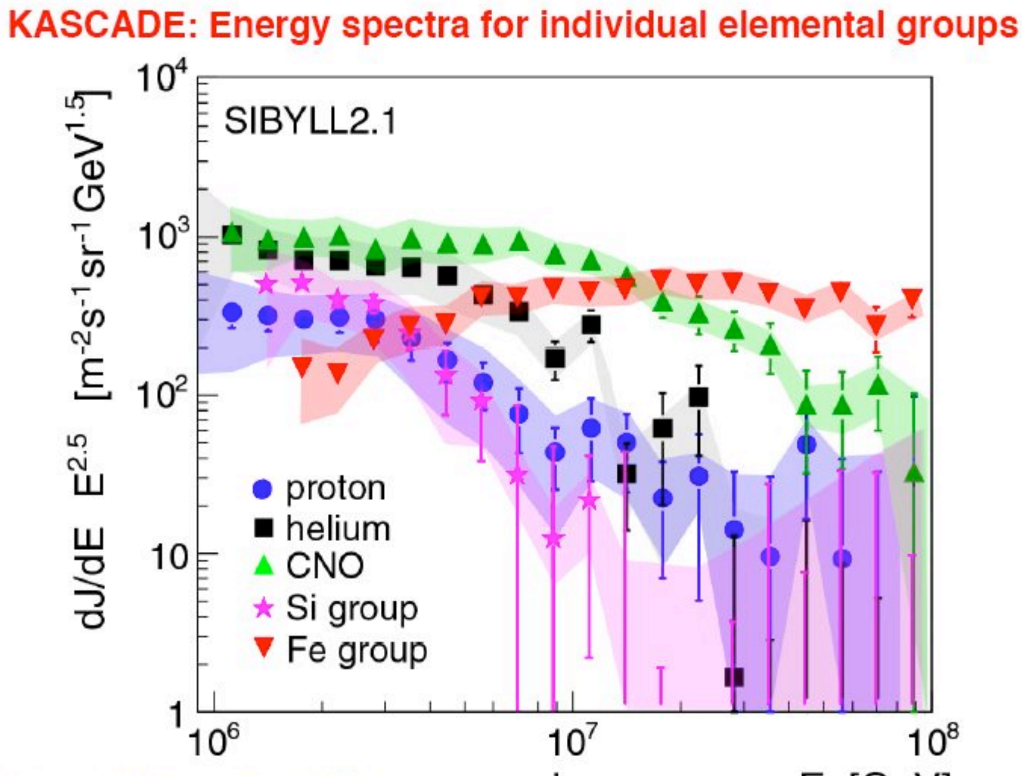
$\text{X}\ E^{2.5} \Rightarrow$

Cosmic ray energy spectrum

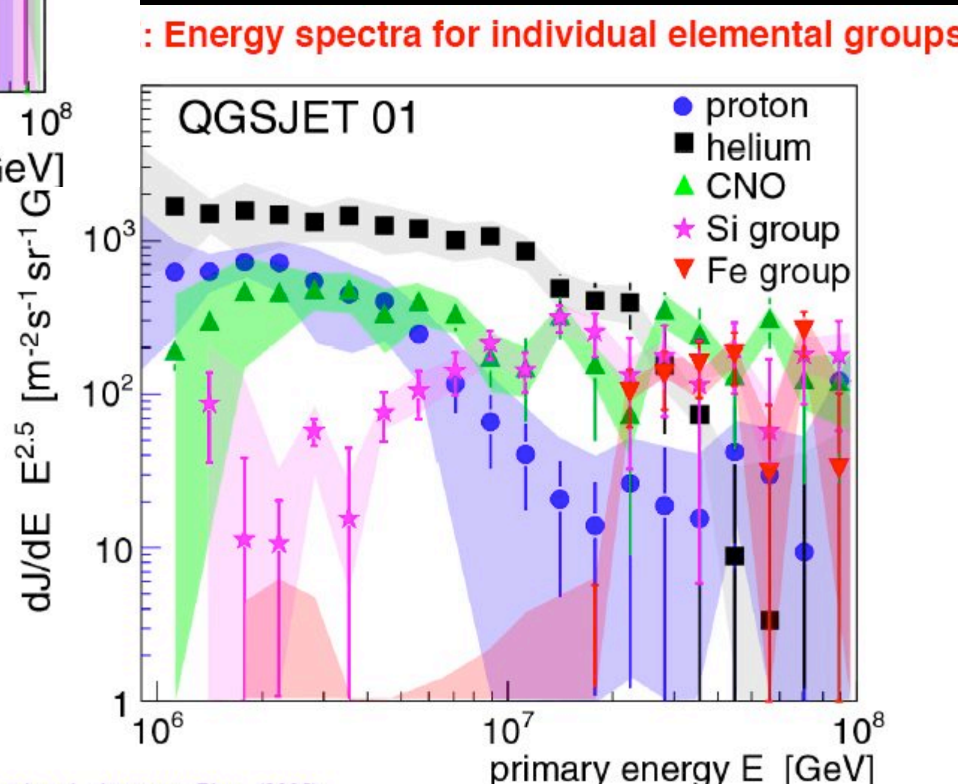


according to Astropart. Phys. 19 (2003) 193

KASCADE Composition at Knee



T. Antoni et al., Astropart. Phys. (2005)



T. Antoni et al., Astropart. Phys. (2005)

Large Uncertainties in Monte-Carlo Simulated Hadronic Interactions

Cosmic Rays Observables

SPECTRUM

COMPOSITION

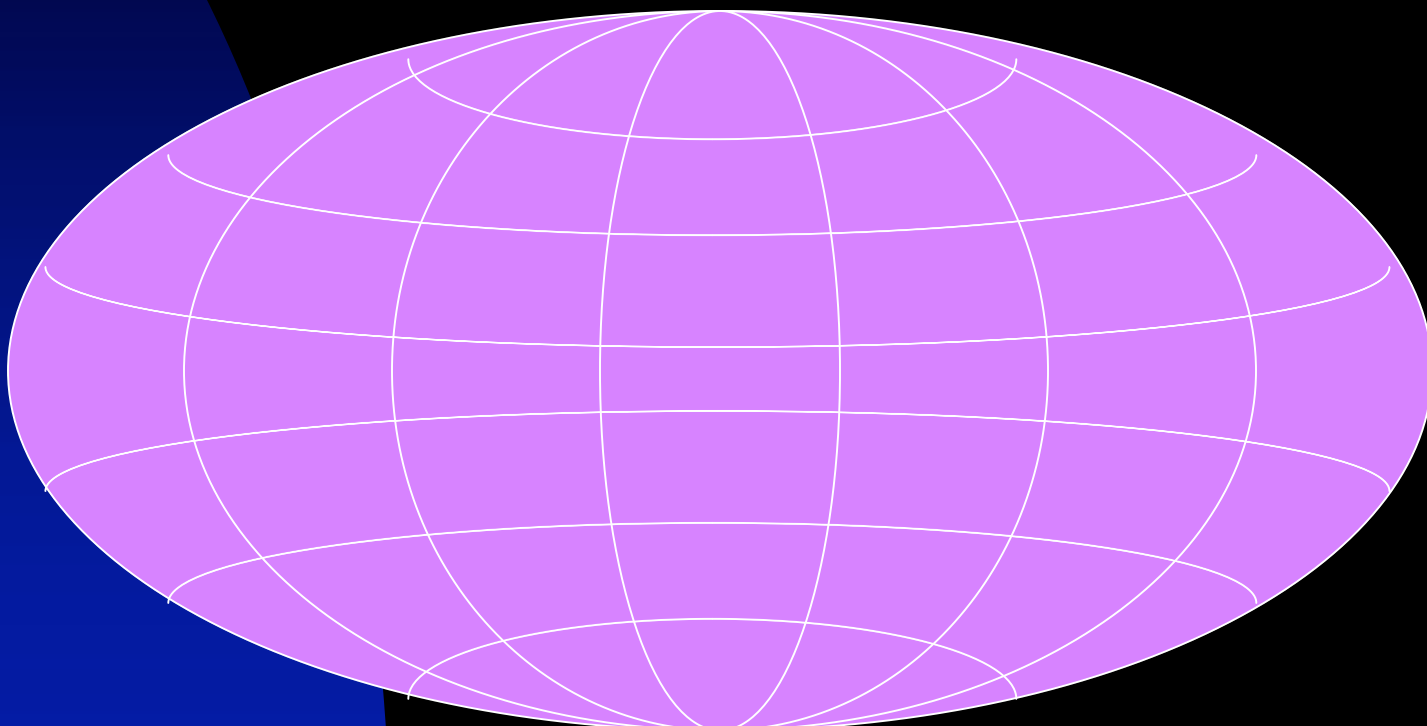
ANISOTROPIES in Sky

MULTIPARTICLE INFO:

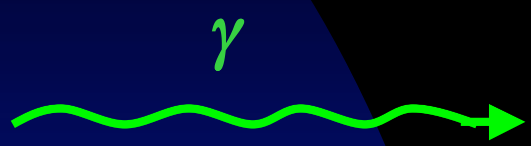
- TeV gamma rays
- Neutrinos

CR arrival directions

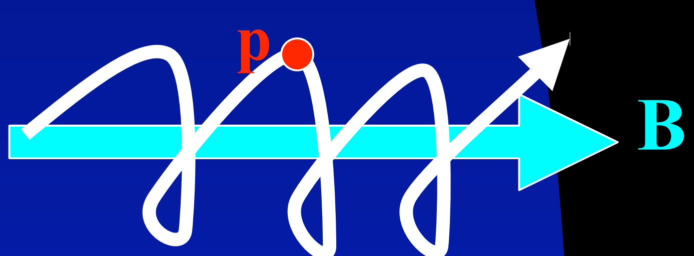
Isotropic!



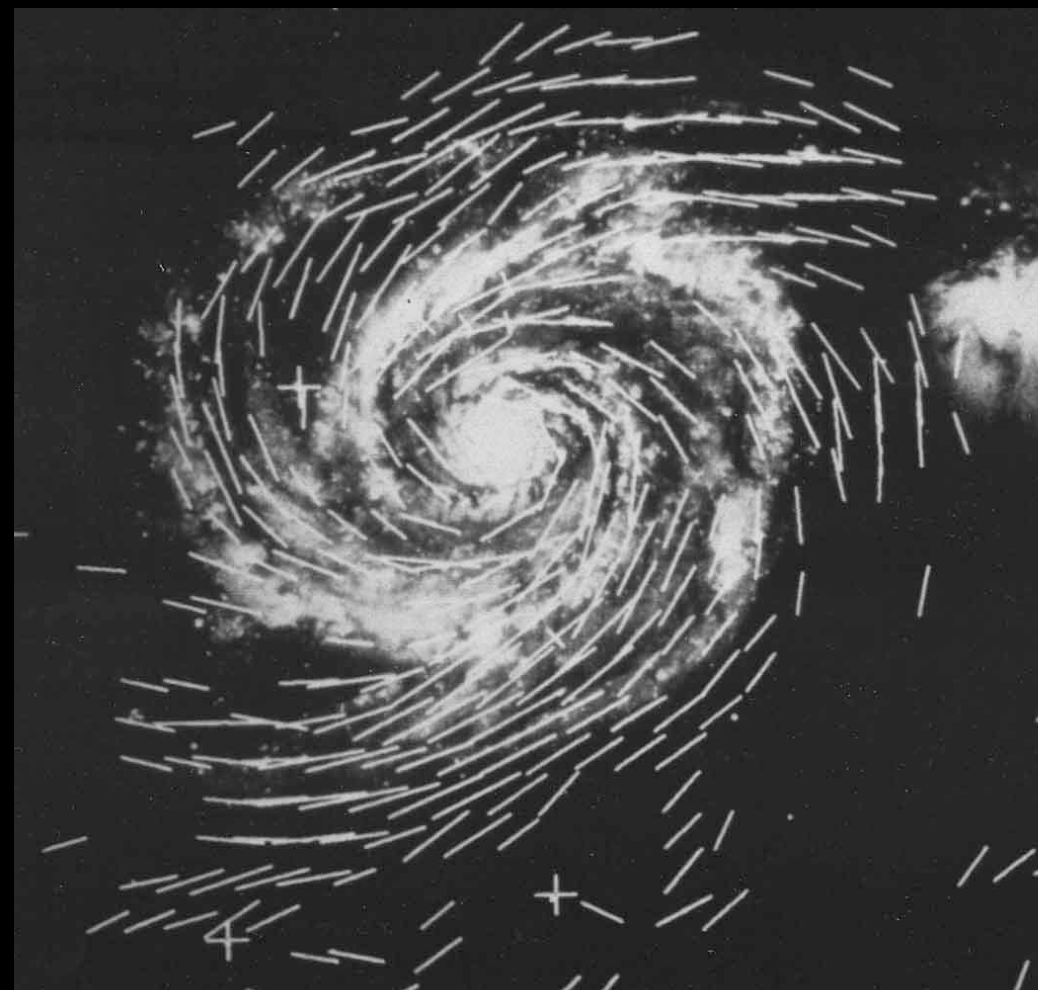
Photons have zero charge
⇒ travel in geodesics
(straightest lines)
point back to source



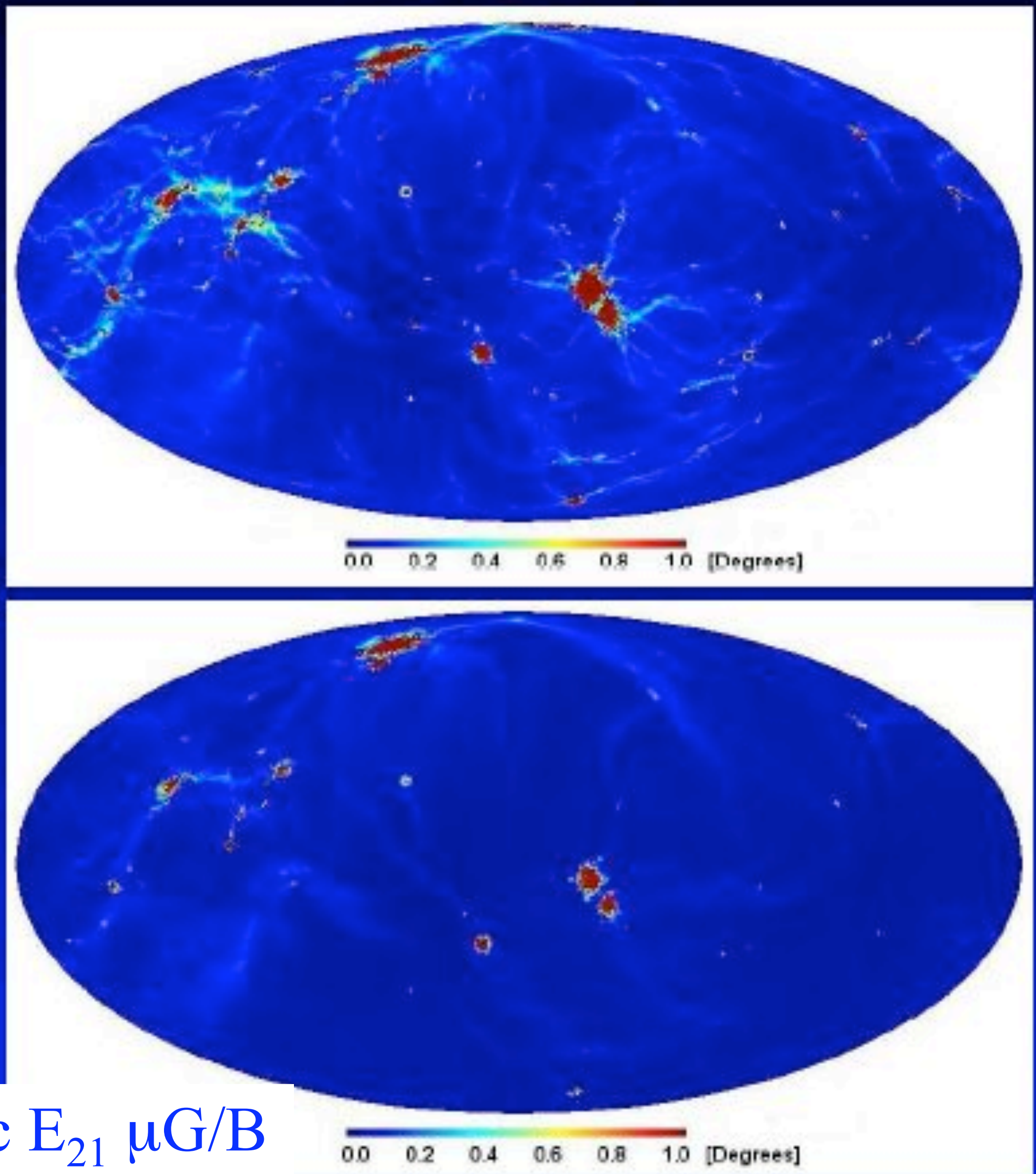
Cosmic Rays are charged
(protons + nuclei)
⇒ deflected by Magnetic Fields
do not point back to source



Galaxies have Magnetic Fields



Astronomy at Energies above ~ 10^{19} - 10^{20} eV



no losses

Dolag et al. 04

with losses

Full sky deflection signal for 1×10^{20} eV Cosmic Rays with and without losses by photo-pion production in collisions with CMB, using a sphere of 100Mpc radius.

R_L=1.1 Mpc E_{21} μG/B

Cosmic Rays Observables

SPECTRUM

COMPOSITION

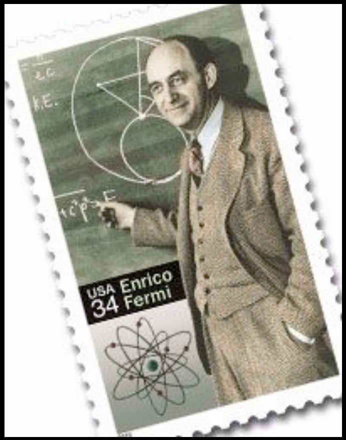
ANISOTROPIES in Sky

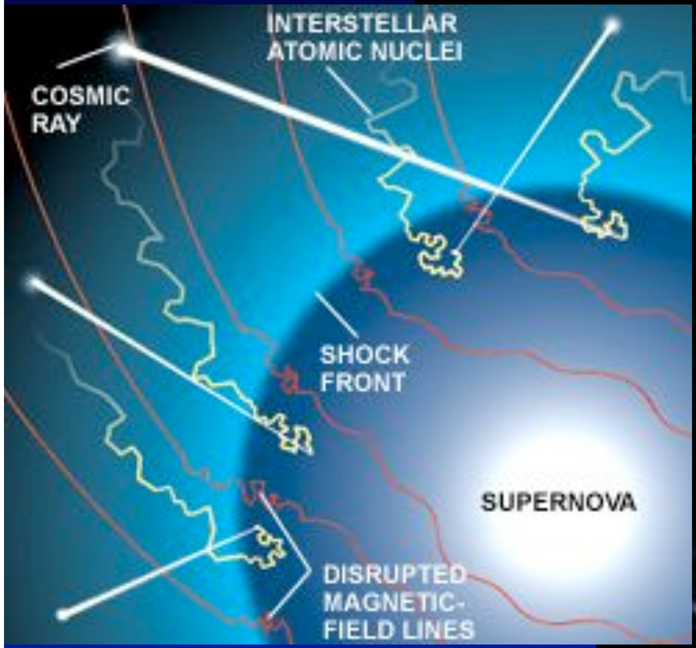
MULTIPARTICLE INFO:

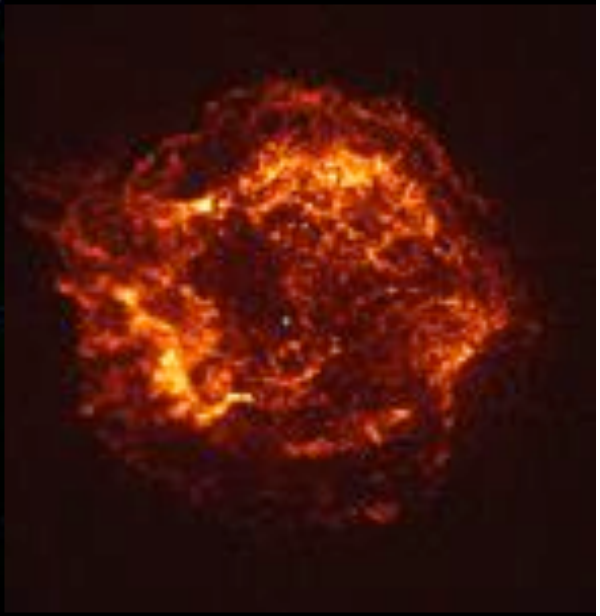
- TeV gamma rays - yes! Gal CRs
- Neutrinos

Cosmic Ray Origin?

Fermi Acceleration in Supernova Shocks
up to ~ 10^{15} eV



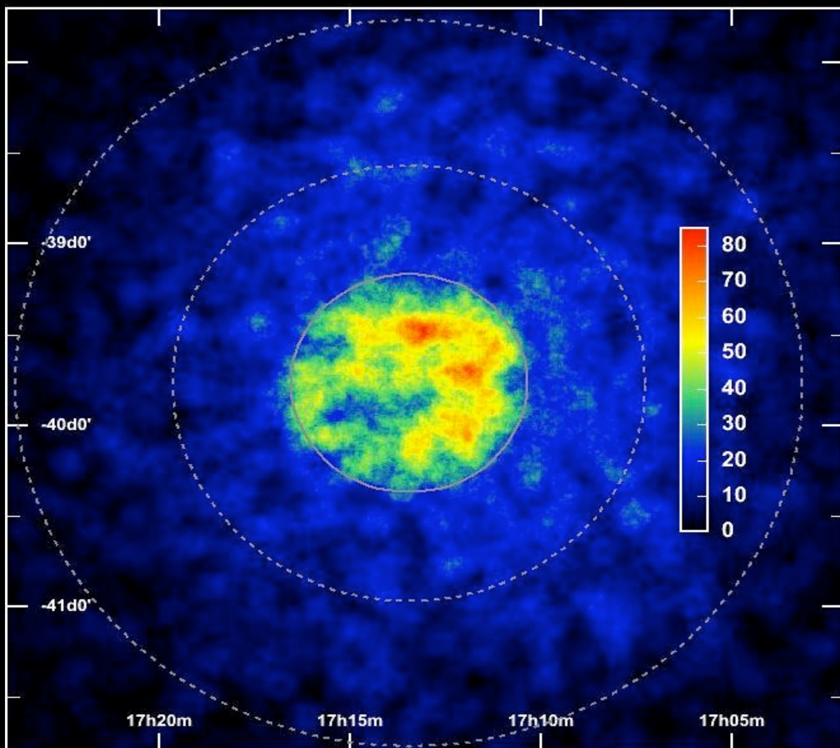




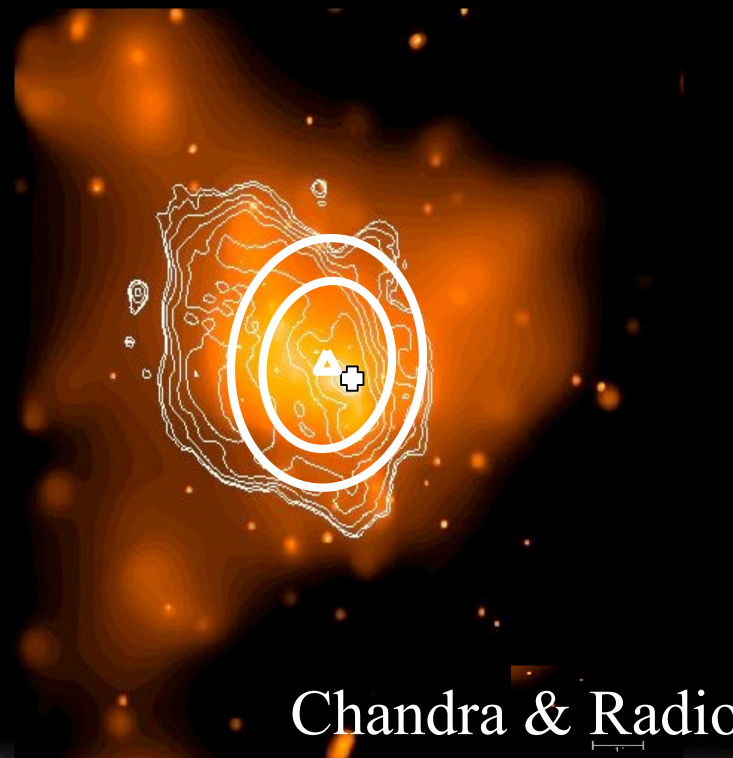
Sources Hidden by Magnetic Fields

HESS - smoking guns in HE γ's ?

RX J1713 - 20 σ



Galactic Centre - 11 σ



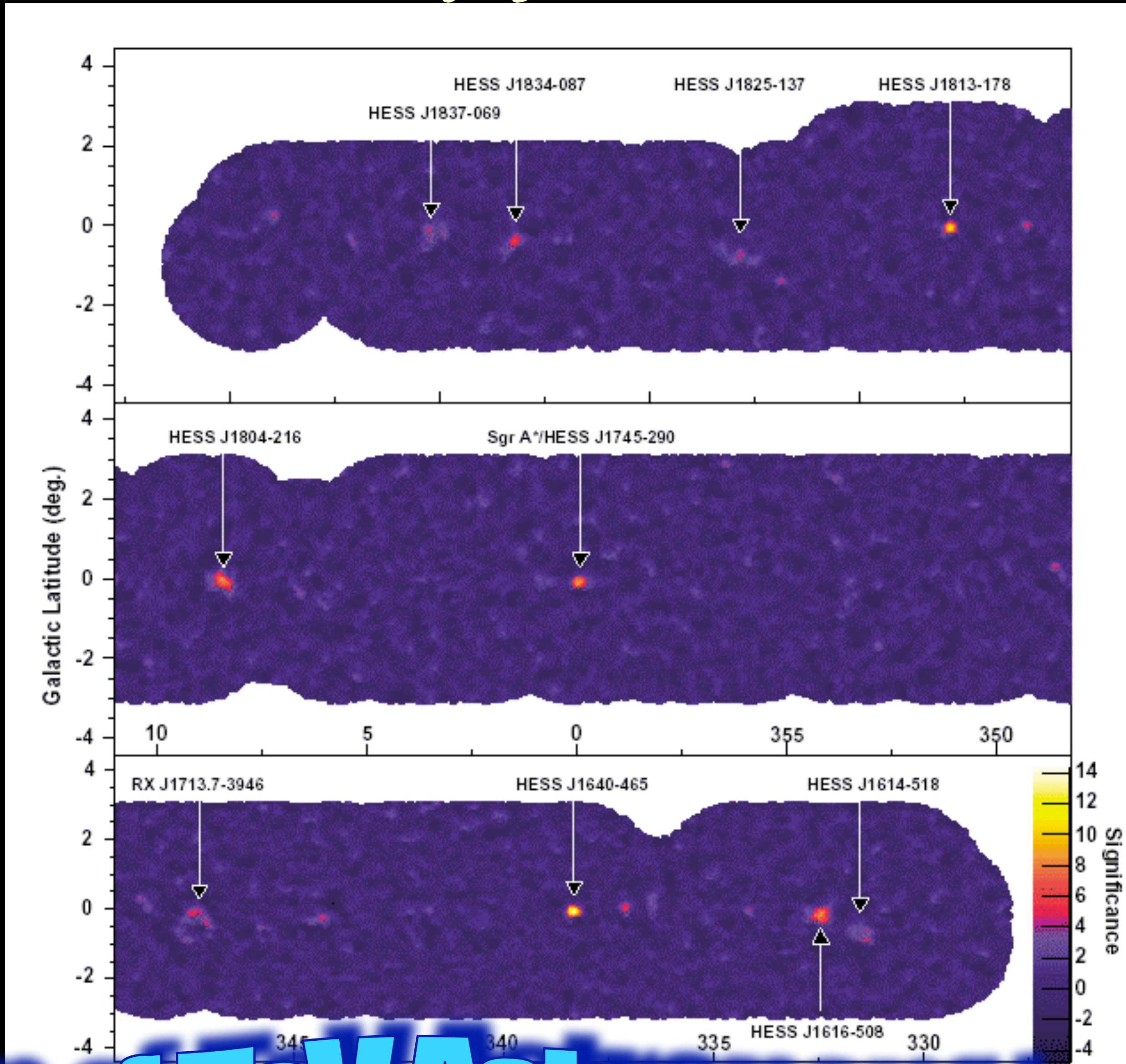
Galactic Plane survey from HESS

8 NEW
TeV gamma-ray sources
some extended

Serendipity:
2 completely unknown
sources discovered

Survey at ~10% Crab
Significances 5->15σ

(Science 3/25/2005)



The dawn of TeV Astronomy

Cosmic Rays Observables

SPECTRUM

+

COMPOSITION

ANISOTROPIES in Sky

MULTIPARTICLE INFO:

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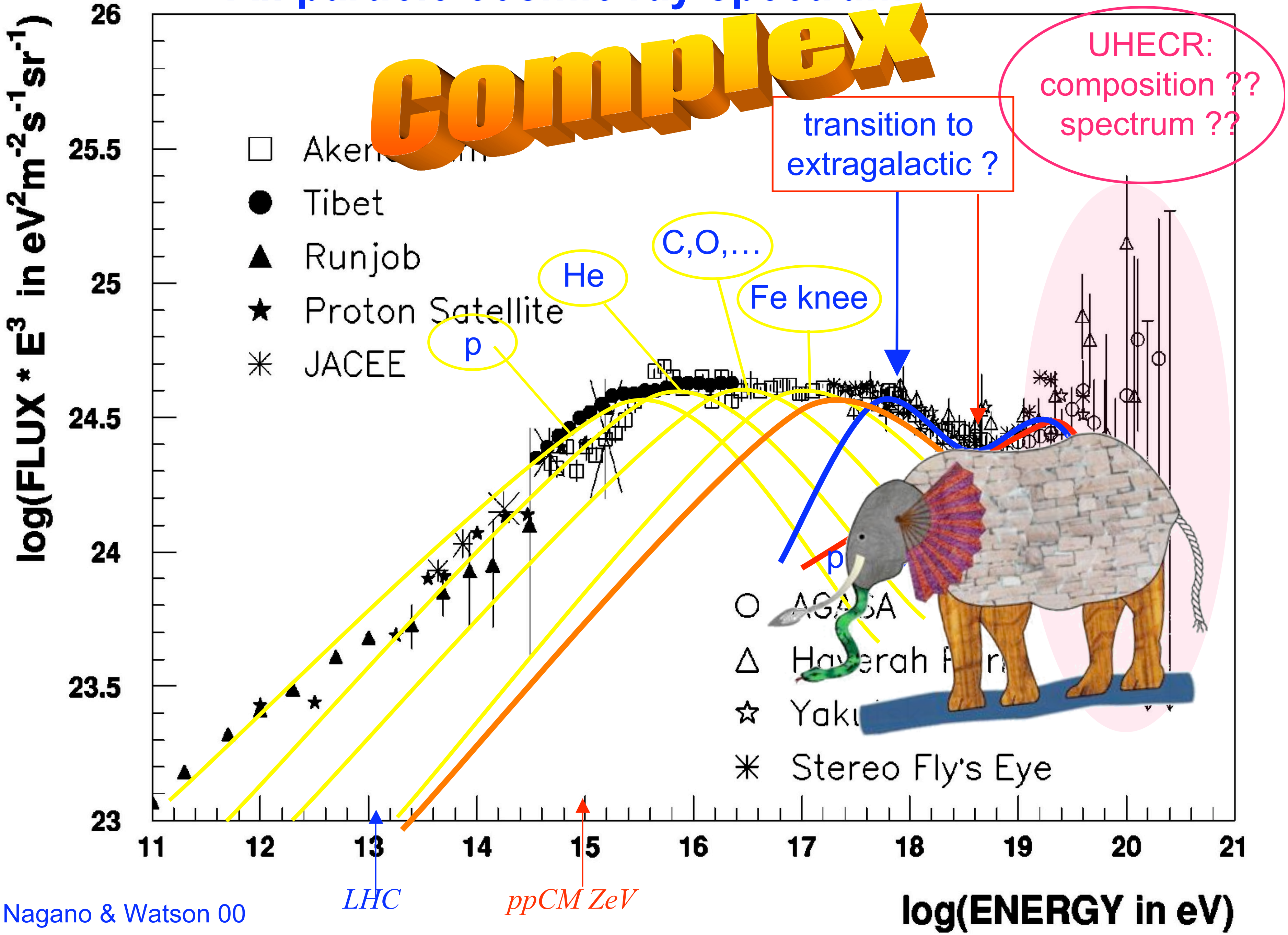
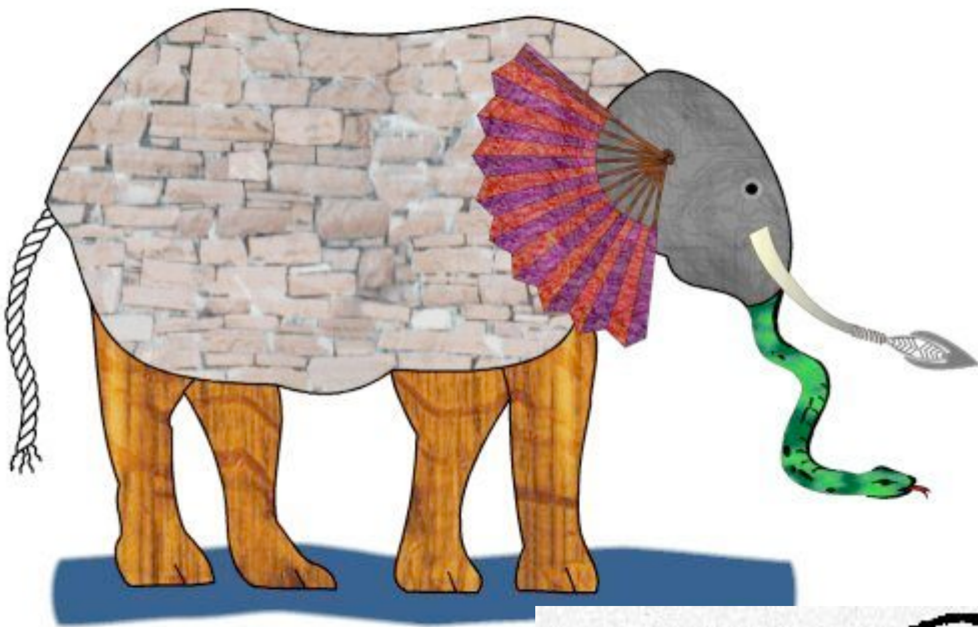
- Neutrinos

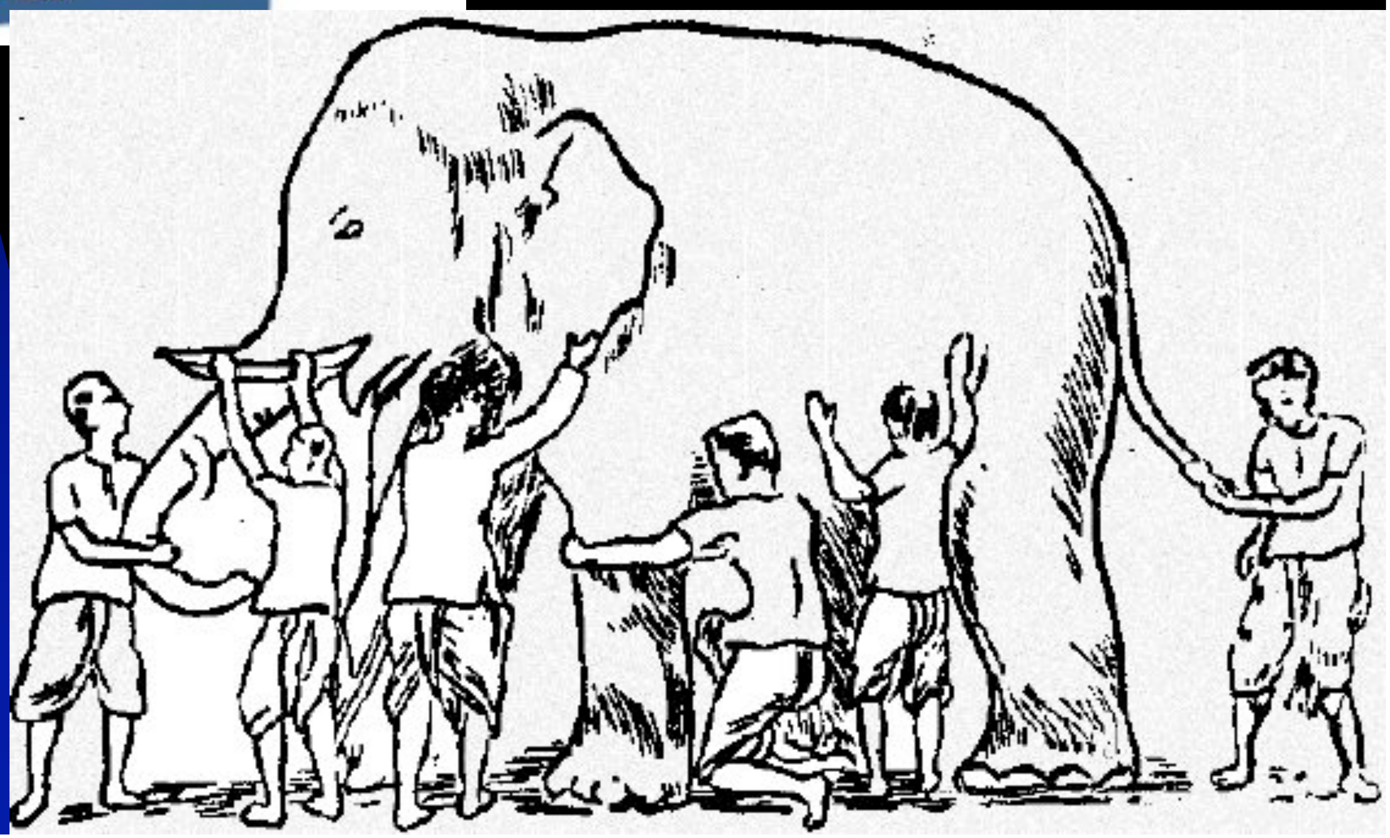
All particle cosmic ray spectrum



Nagano & Watson 00



6 blind men describe an elephant…



UHECRs

Ultra High Energy Cosmic Rays

10^{18} eV (= EeV) to > 10^{20} eV

Highest energy particles ever observed

Hadron-like - protons &/or heavier nuclei

Observed through airshowers

Origin Unknown - Astrophysical &/or Physical Puzzle

Anisotropies expected ~ 10^{19} eV and 10^{20} eV

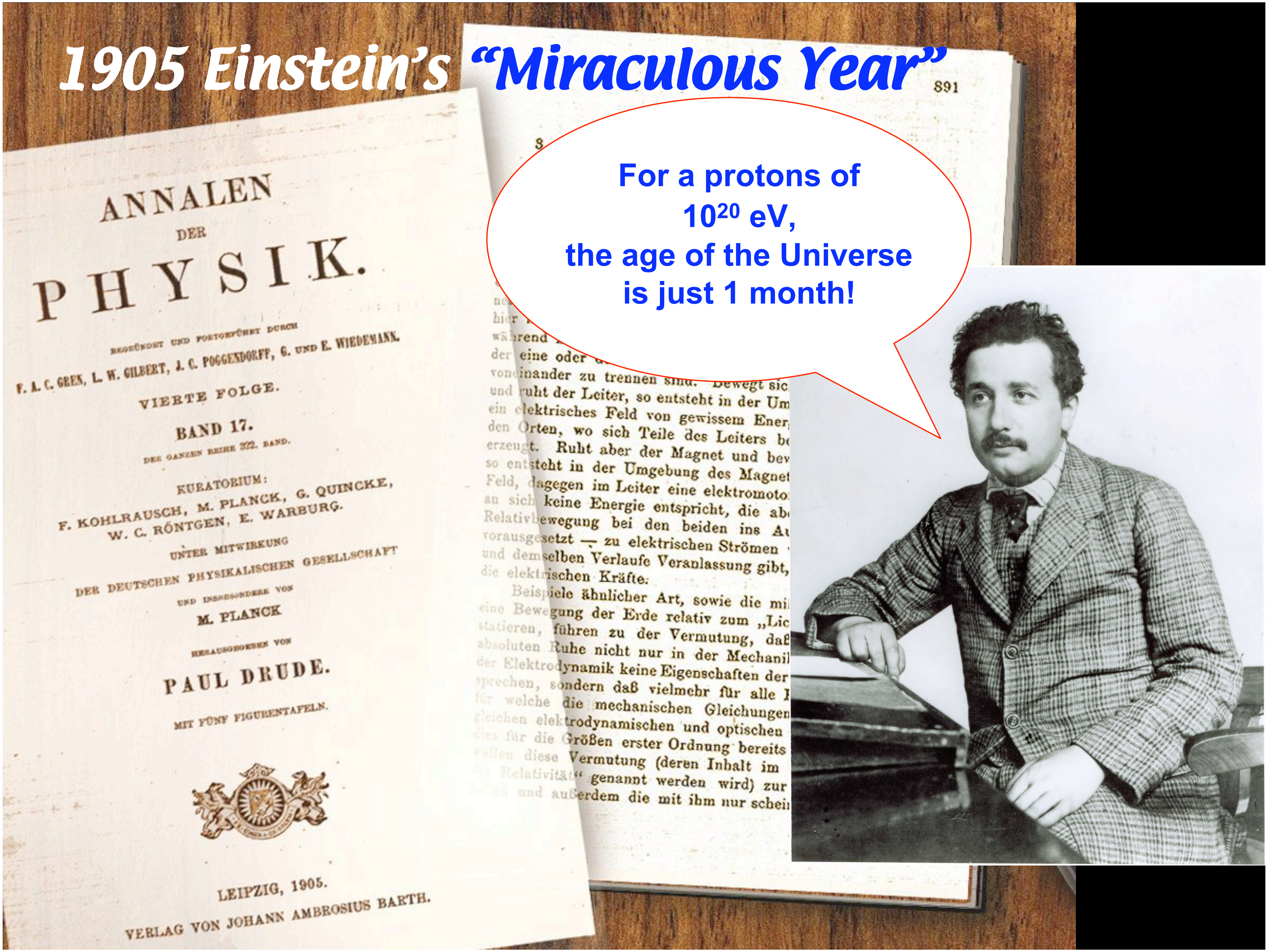
Power law spectrum + features expected

UHECRs (+ CMB) generate UHE neutrinos

UHECRs & UHEν's useful to test

Particle Physics Interactions & Relativity

1905 Einstein's "Miraculous Year"



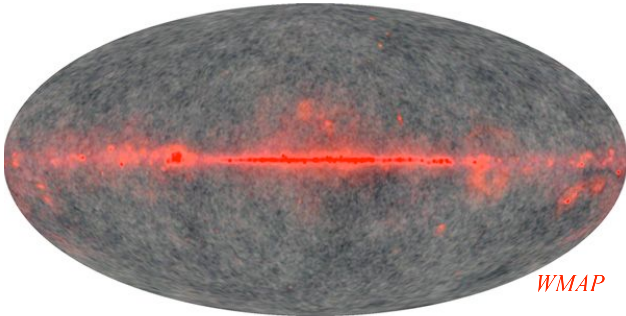
Expectations

Determine their ORIGIN

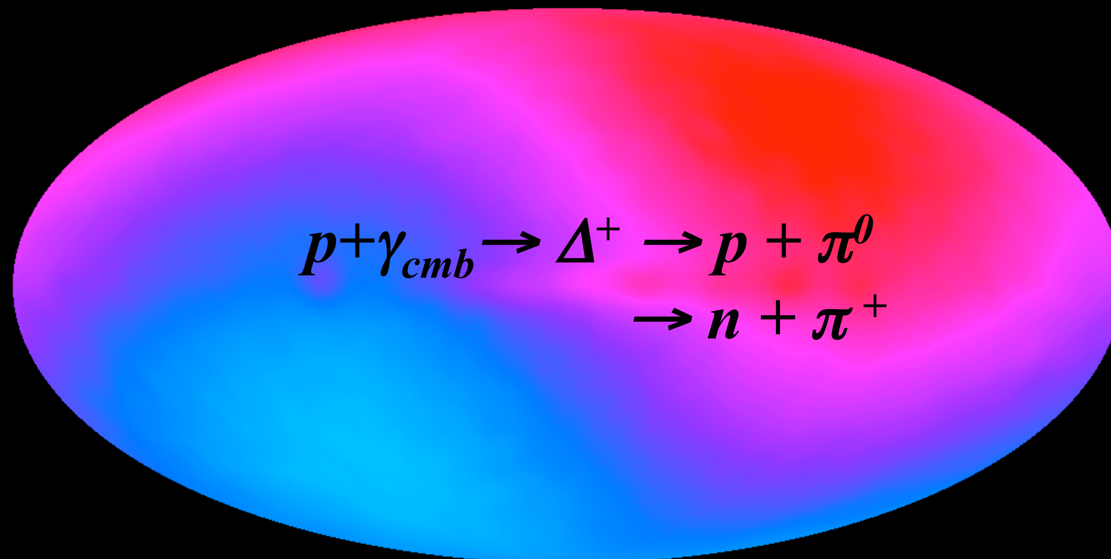
- Highest energy accelerators in Universe:
  - Super Massive Black Holes?
  - Relics of the Early Universe?

- Determine Composition
- Determine Spectral Features
- Observe Anisotropies in the sky distribution or arrival directions

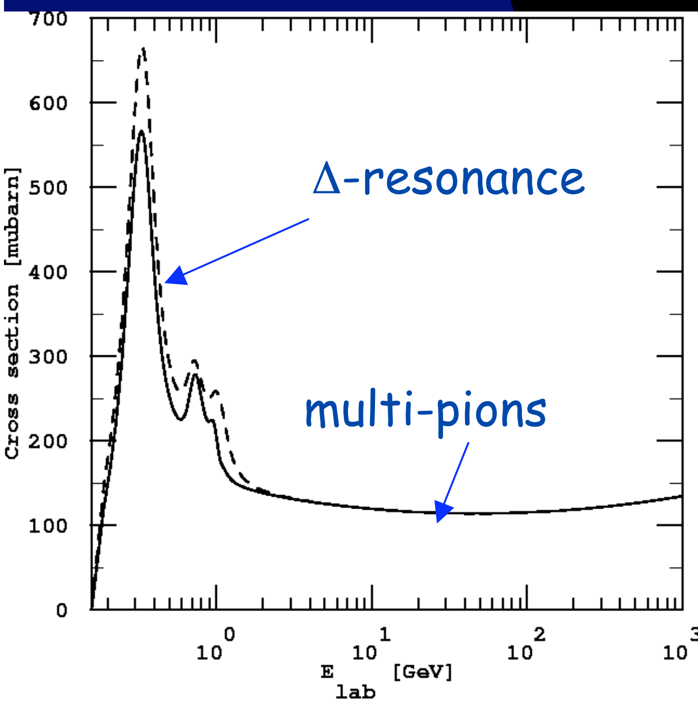
High Energy Proton sees Cosmic Microwave Background as High Energy Gamma Rays!



Proton Horizon



$$p+\gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$



GZK Cutoff

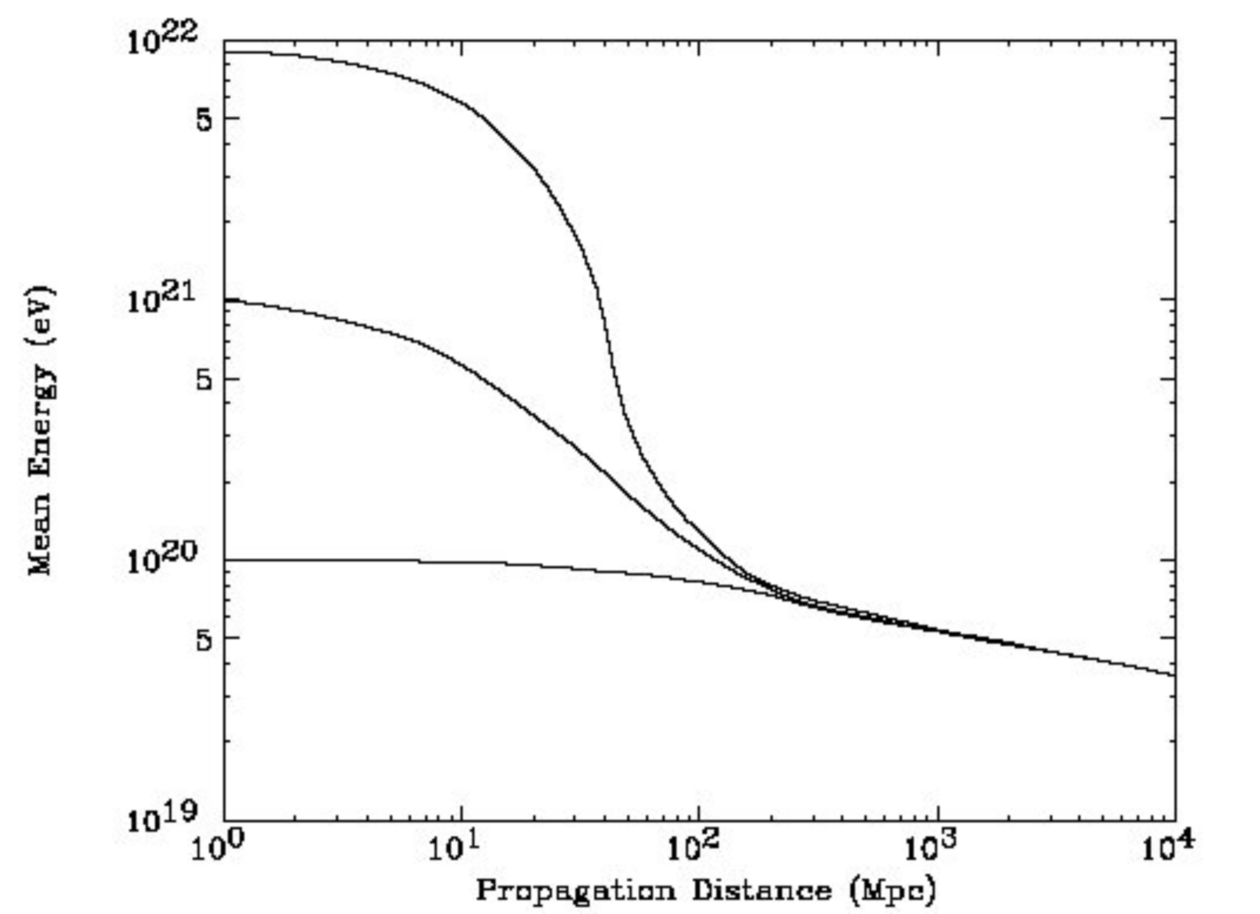
Greisen '66, Zatsepin & Kuzmin '66

Extragalactic UHE Protons Propagation

Photo Pion production off

cosmic microwave background (CMB)

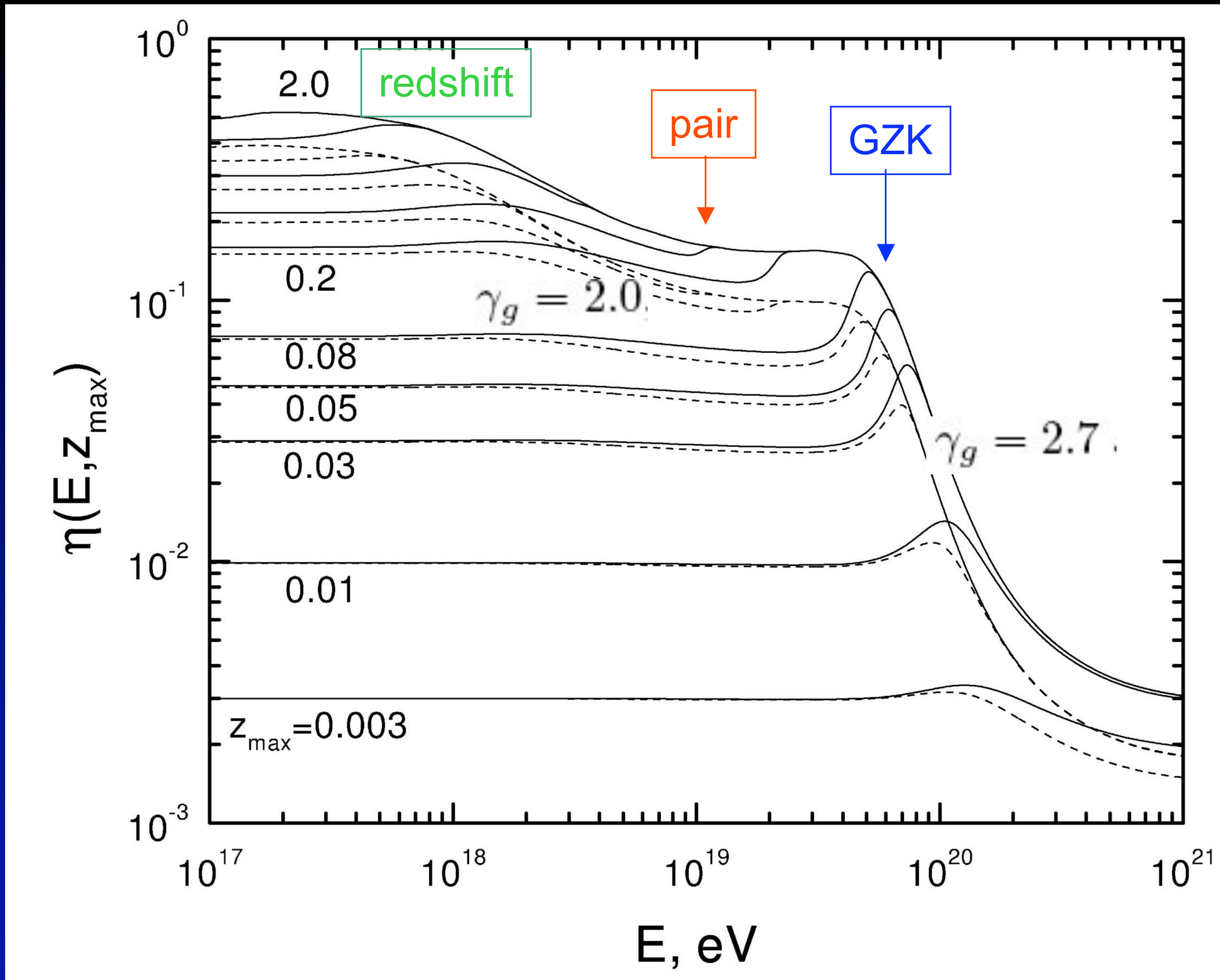
$p+\gamma_{cmb} \rightarrow \Delta \rightarrow p/n+\pi$



Proton energy vs. distance (J. Cronin)

Energy losses for protons

Berezinsky et al. 03



modification factor: $J_{obs}(E,z) = \eta(E,z) \times J_{injec}(E)$

Expectations

Determine their ORIGIN

Highest energy accelerators in Universe:

Super Massive Black Holes?

Relics of the Early Universe?

Determine Composition

Determine Spectral Features

Observe Anisotropies in the sky distribution of arrival directions

Challenge: to reach > 10^4 - 10^5 km^2 sr yr

Present experiments ~ 10^3 km^2 sr yr

Old Data

Challenge: to reach > 10^4 - 10^5 km^2 sr yr

Present experiments ~ 10^3 km^2 sr yr

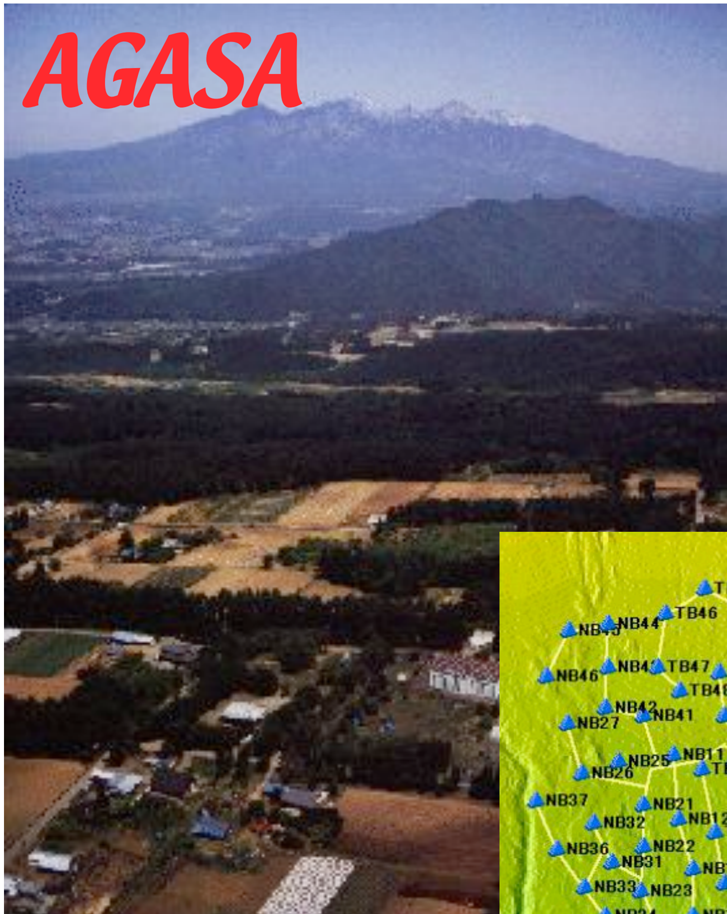
AGASA (100 km^2 array scintillators)

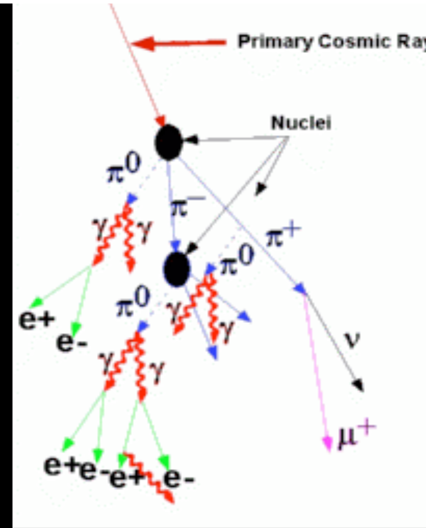
exposure ~ 1.6 10^3 km^2 sr yr

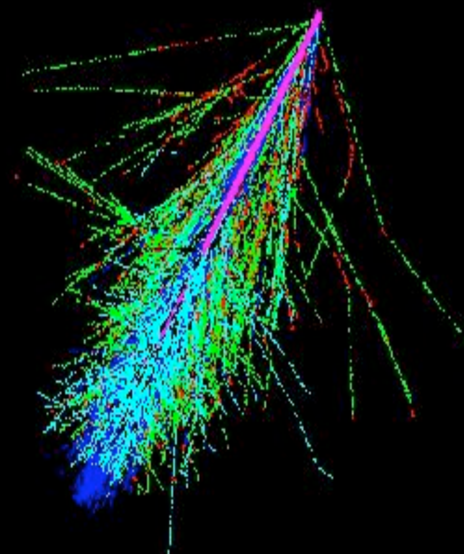
HiRes (Binocular Fluorescence Telescopes)

exposure ~ 2 10^3 km^2 sr yr

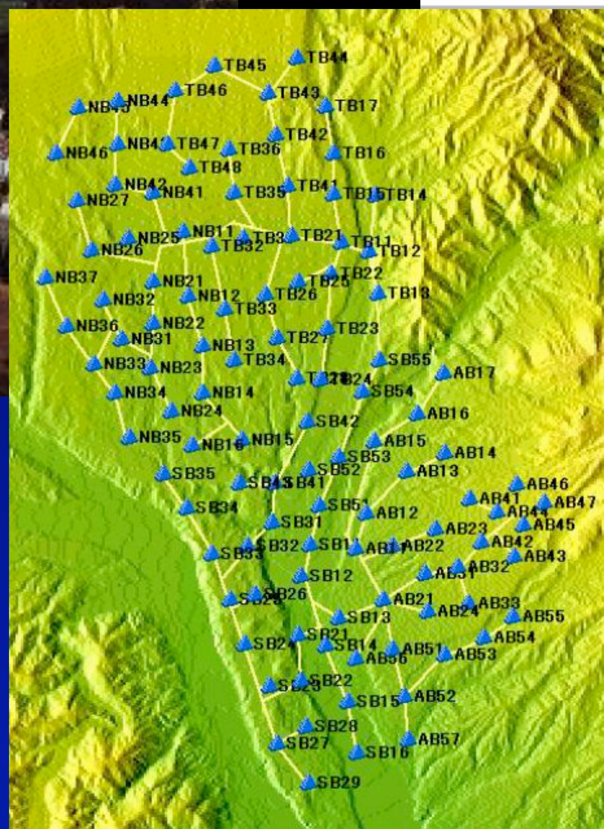
Controversy over spectrum & anisotropies

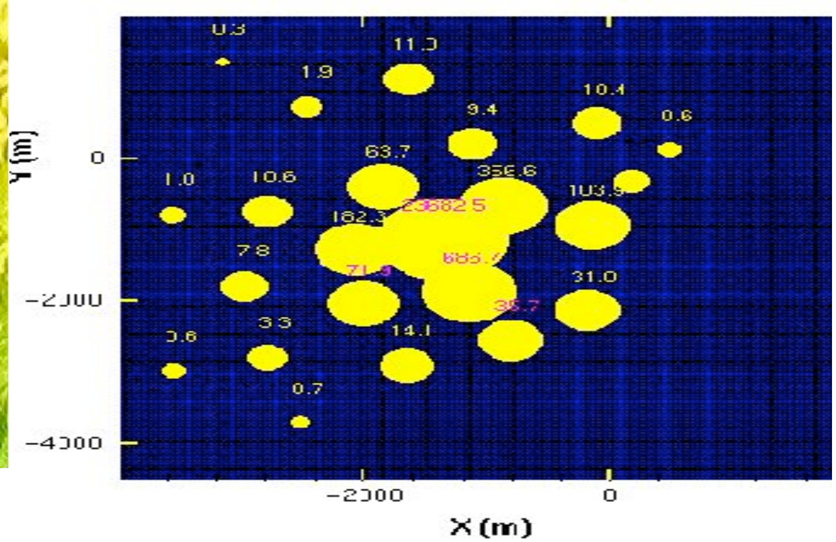






100 km^2
scintillators
+ muon
detectors





Ground Arrays:

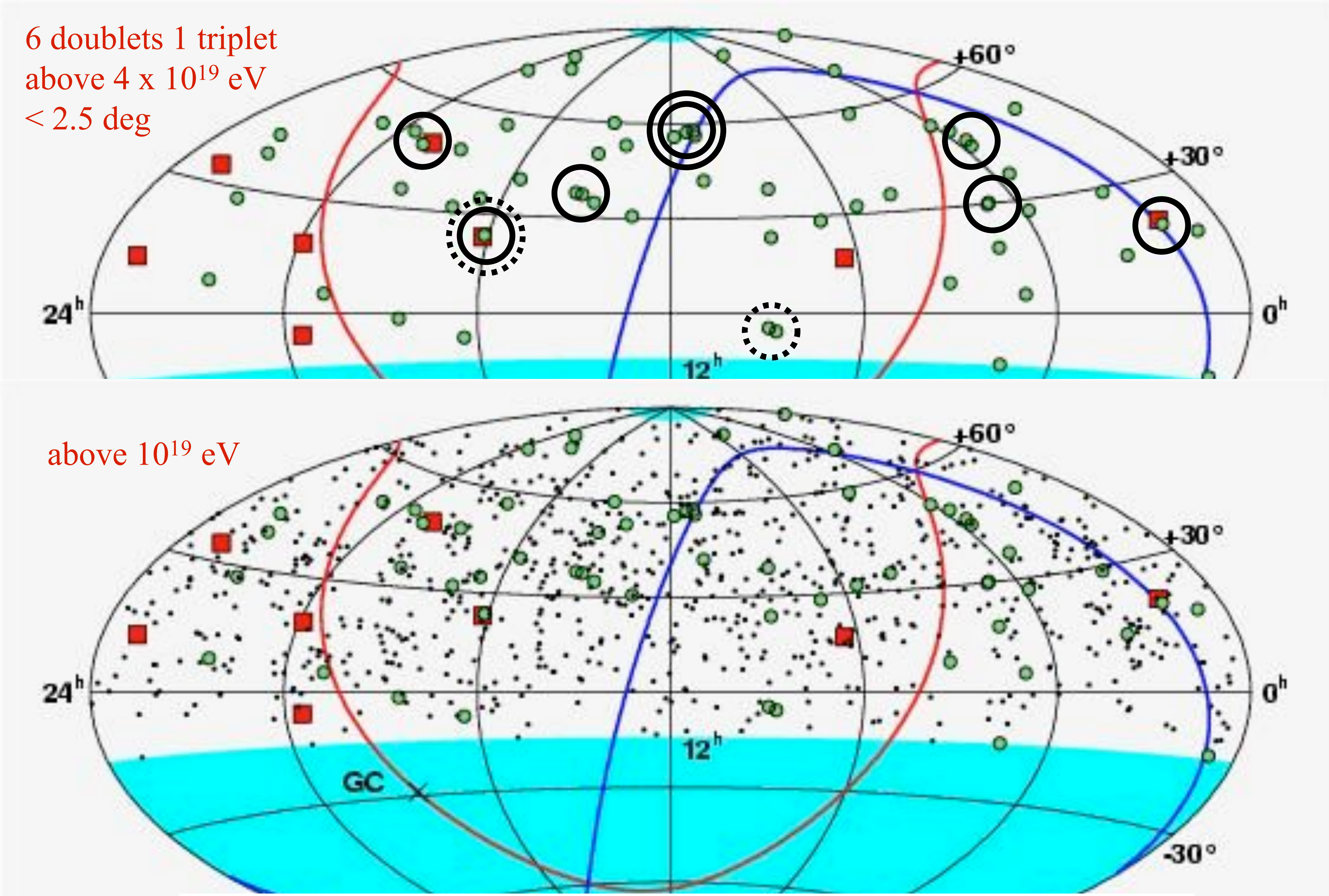
Volcano Ranch

Yakutsk

Haverah Park

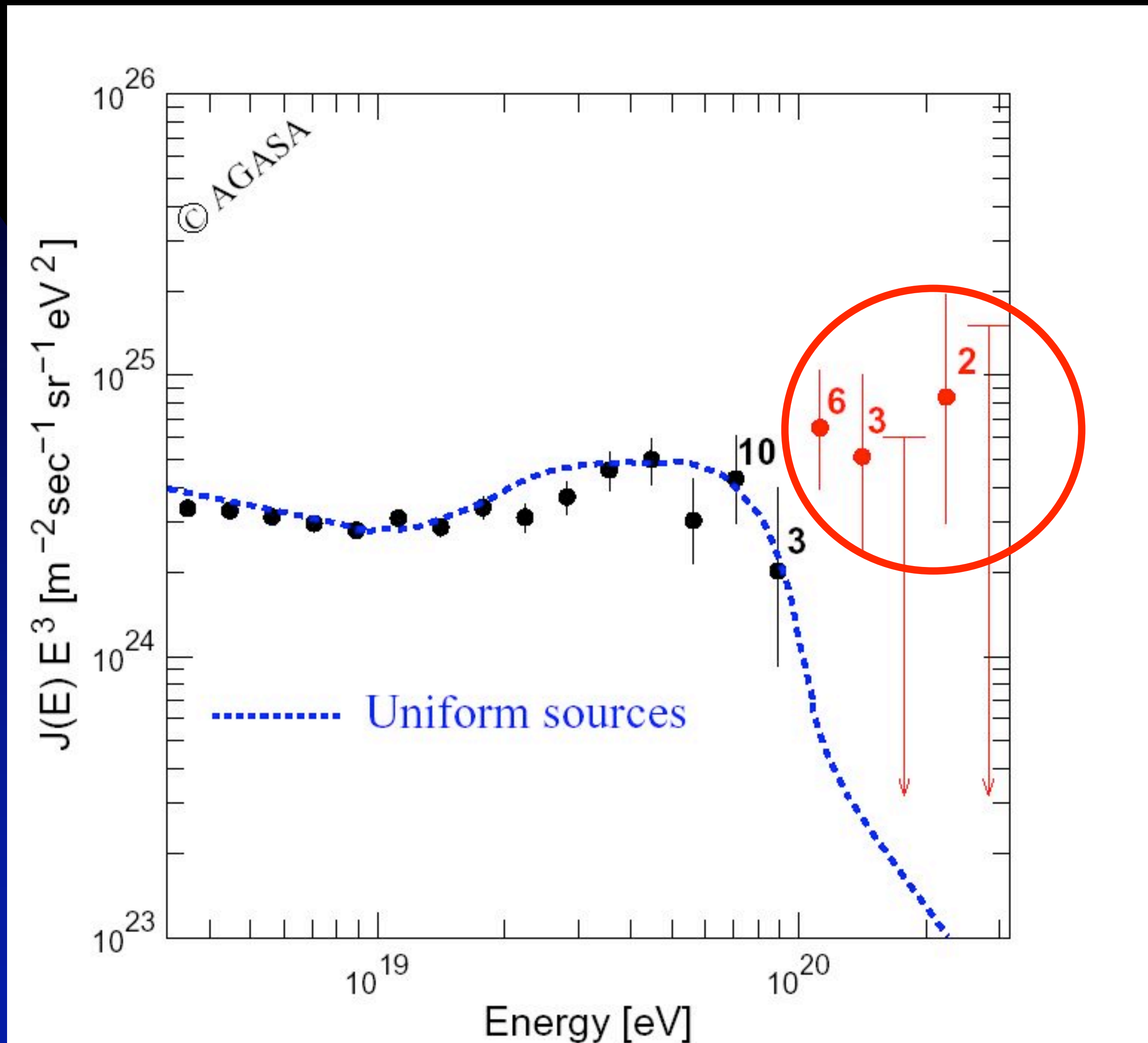
SUGAR

Akeno

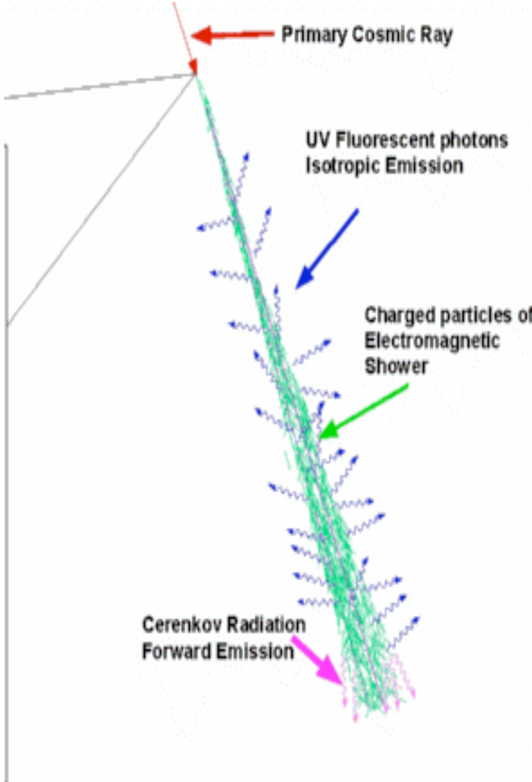


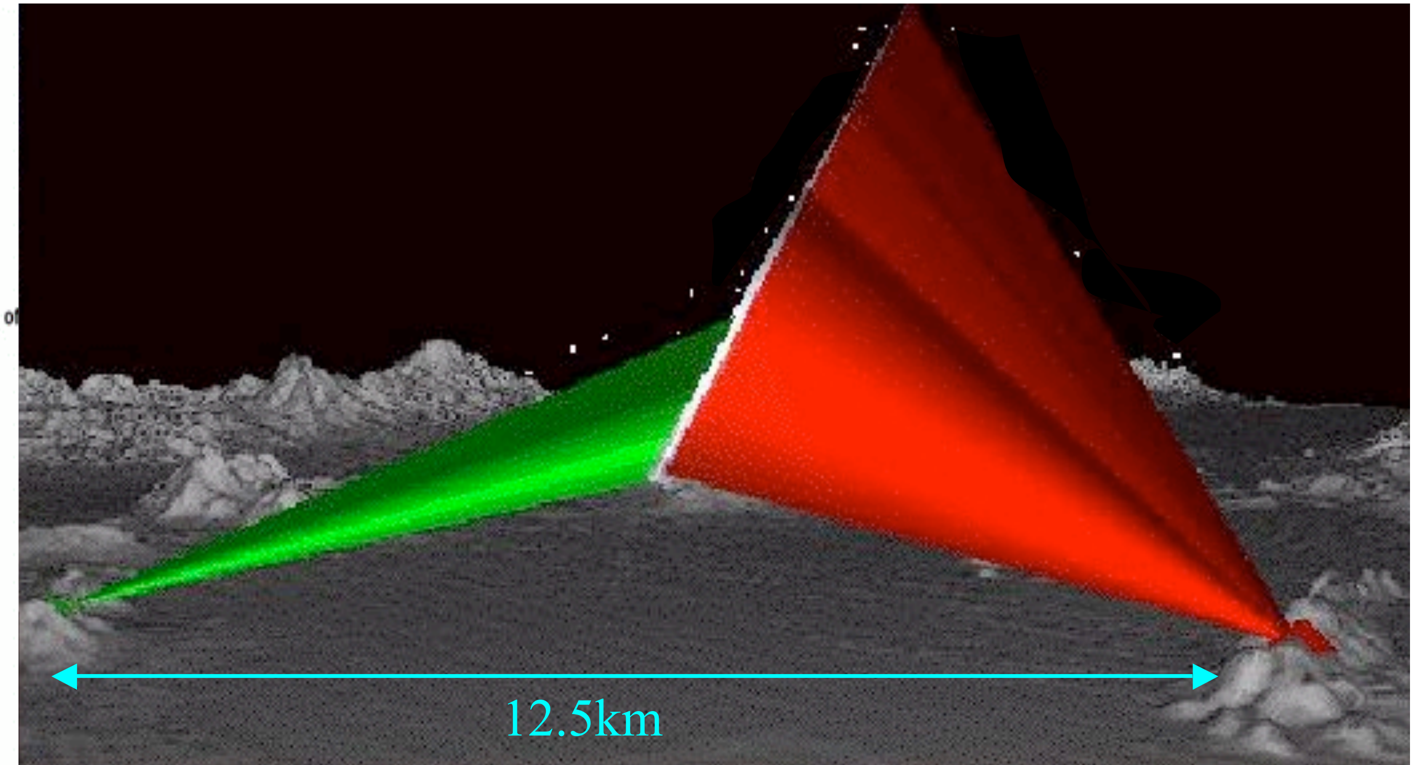
First Hints of Extragalactic Proton Sources?

Observed High Energy Spectrum

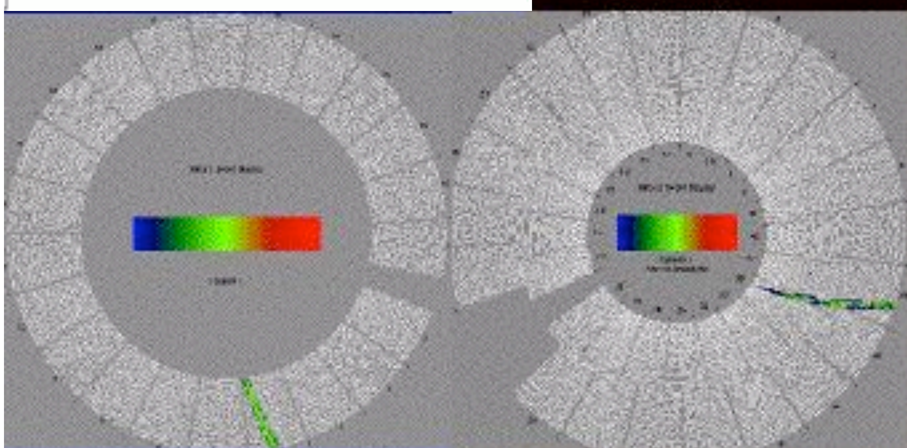


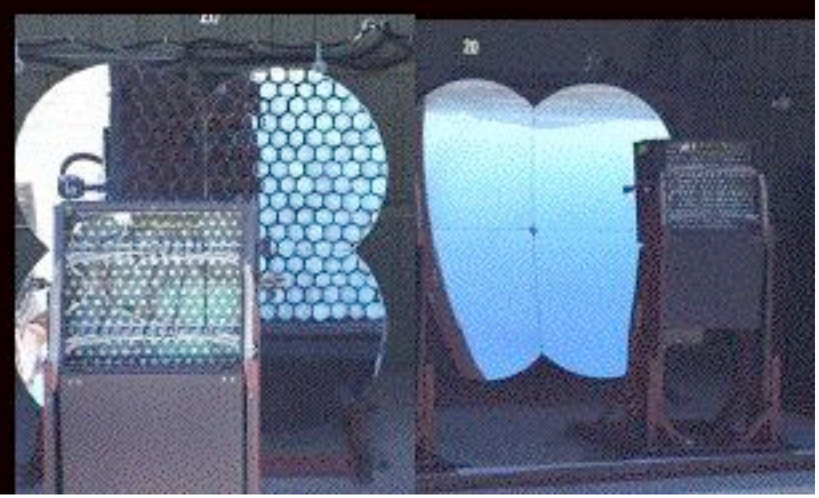
AGASA: ~ 11 events above 10^{20} eV!!!





High Resolution Fly's Eye



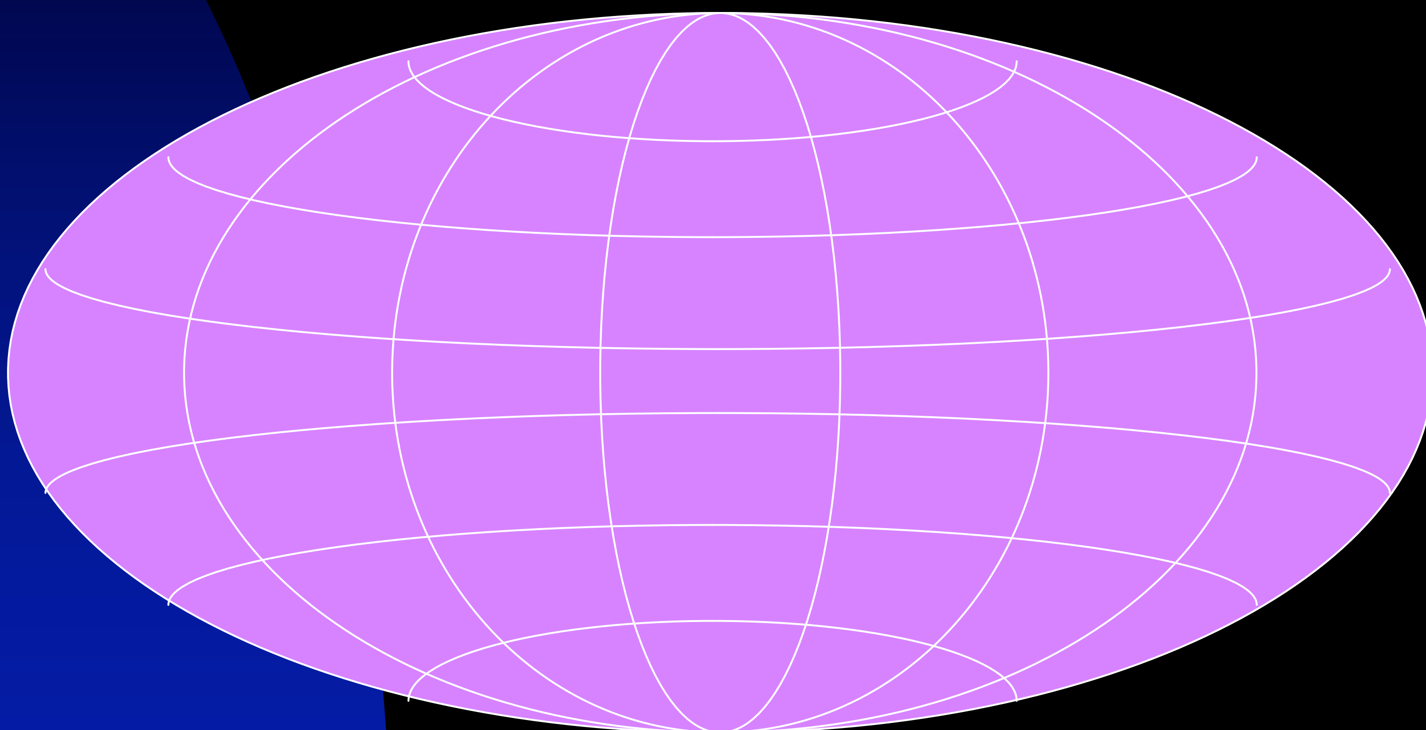


Pioneer Fluorescence Detector:

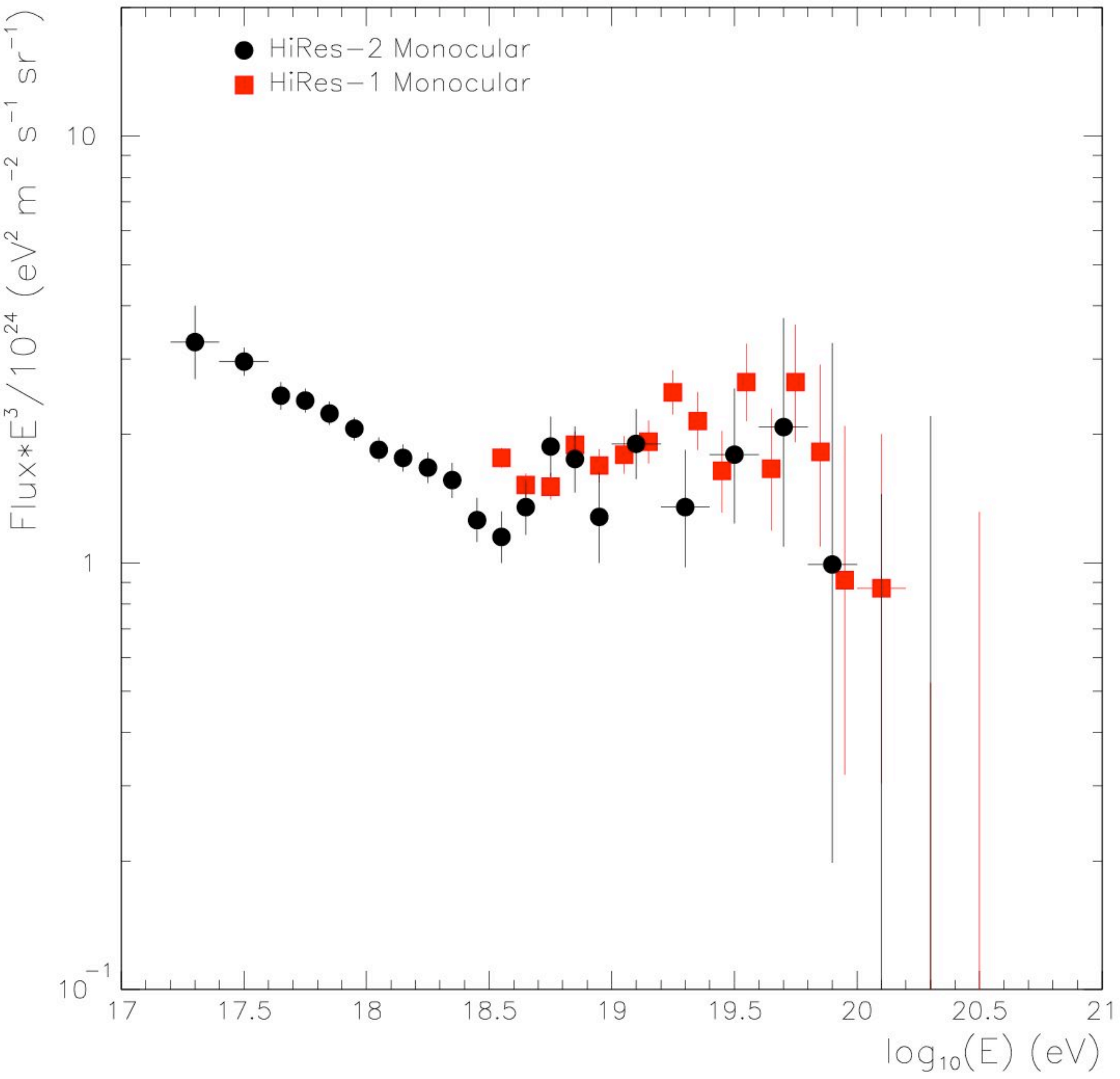
Fly's Eye

CR arrival directions

Isotropic! No counterparts!



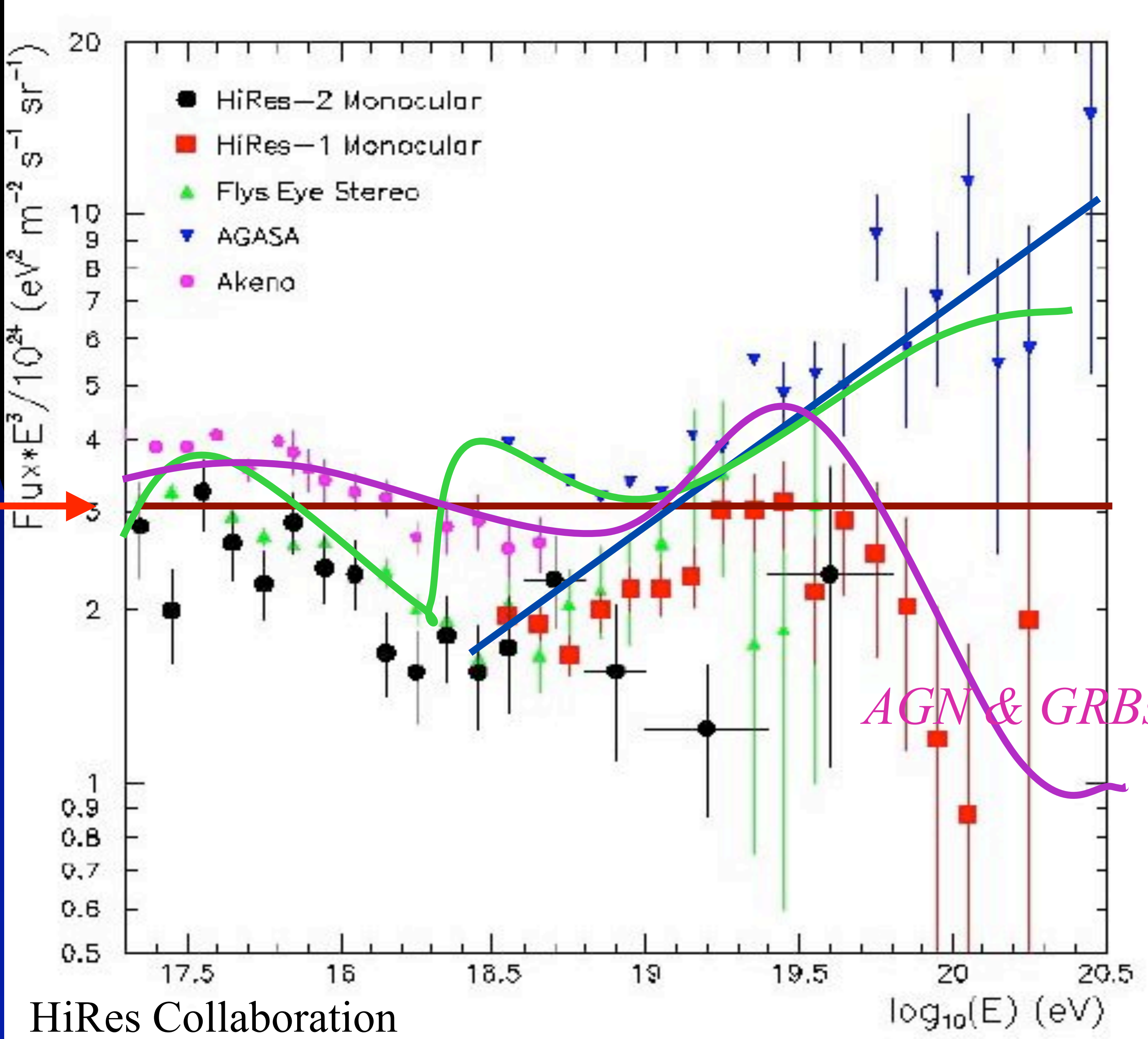
HiRes Spectrum 2003



A Theorist's Field Day

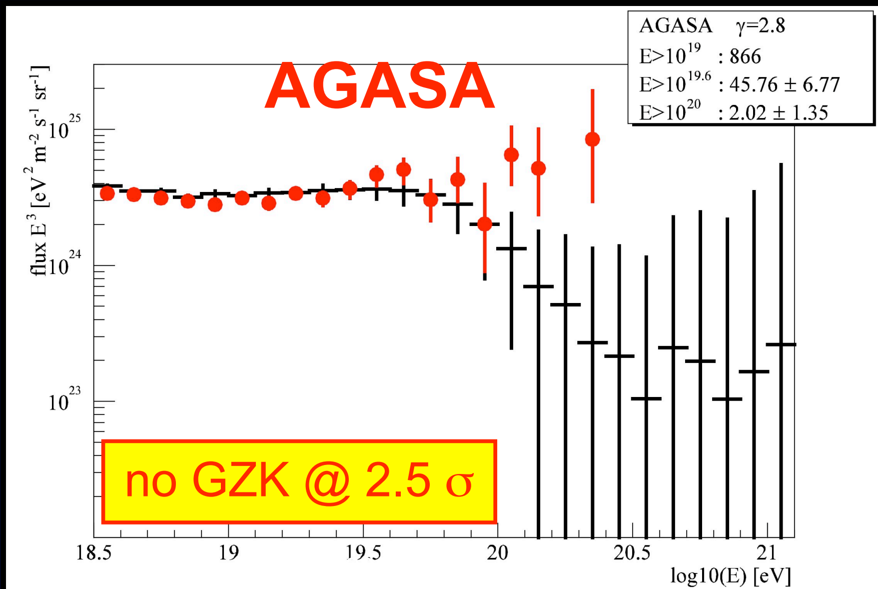
HiRes + AGASA

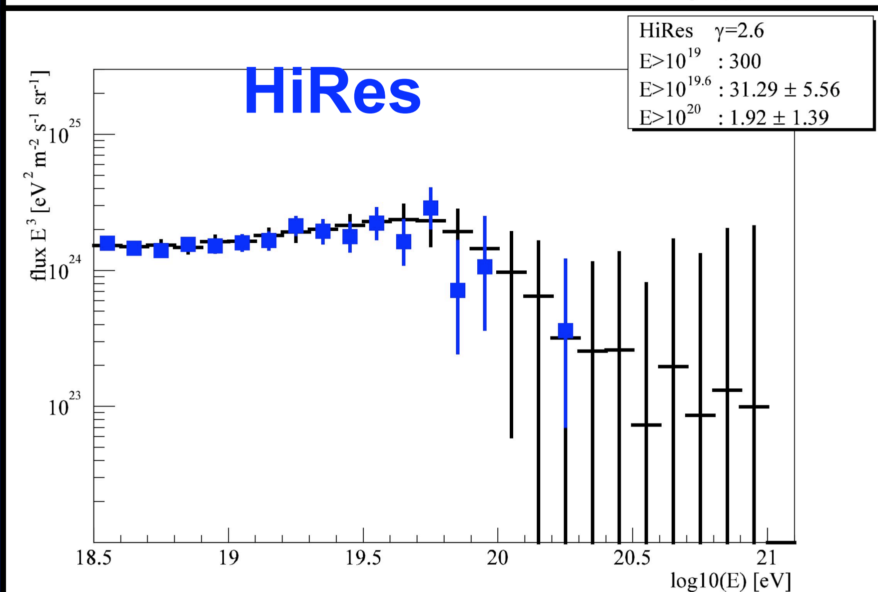
Lorentz Invariance Violation



HiRes Collaboration

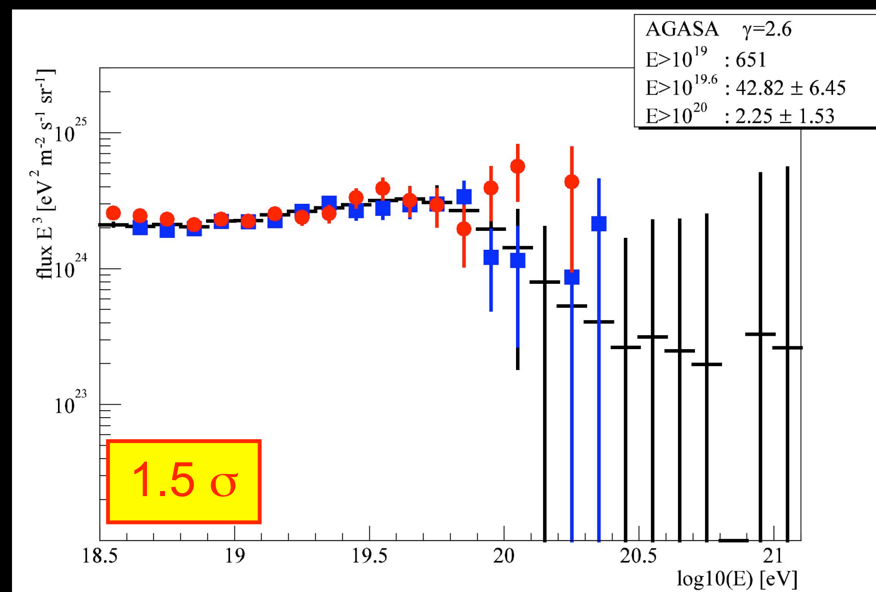
Low Statistics + systematic errors





AGASA-15%

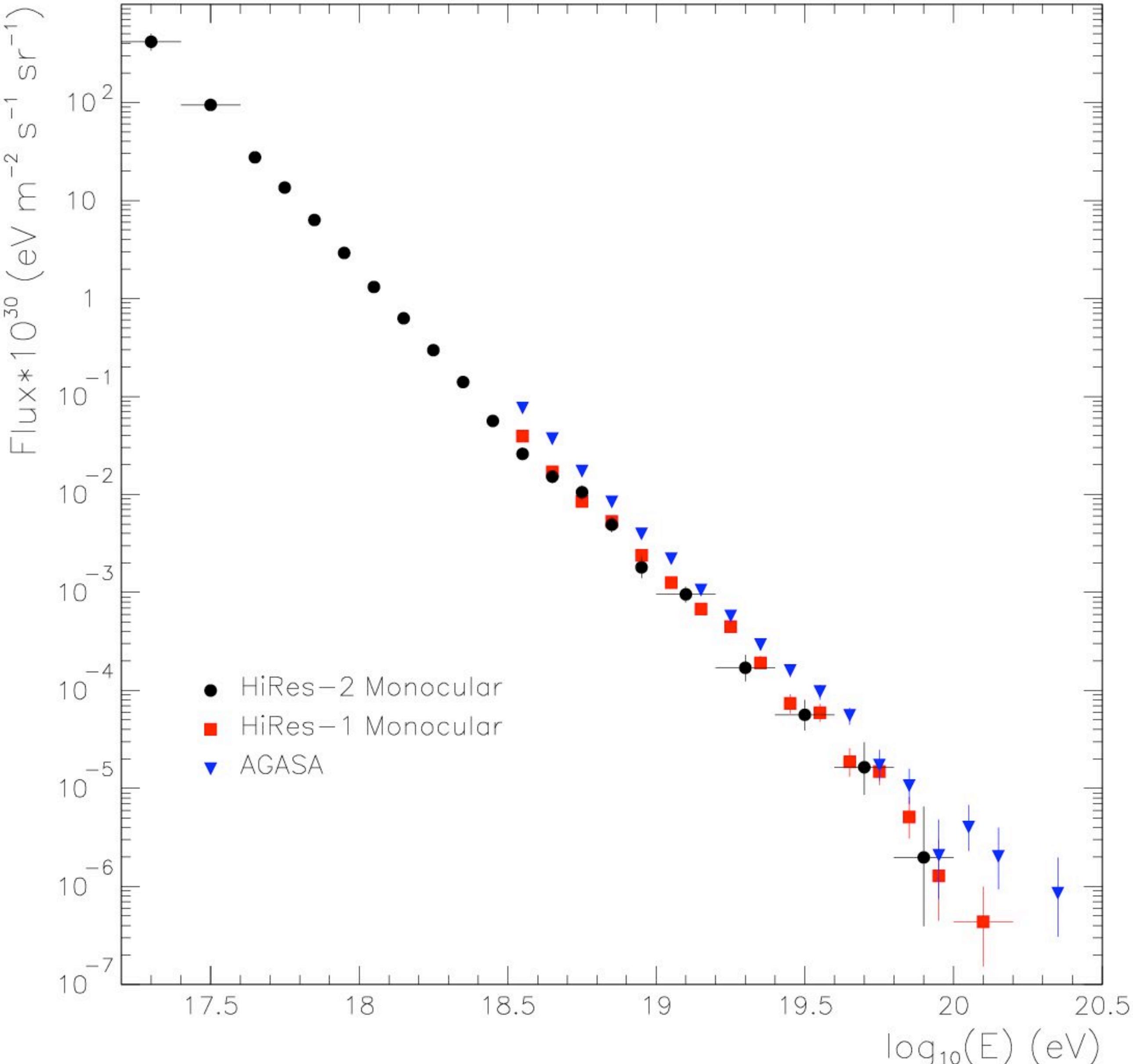
HiRes +15%



$E_{max}=10^{21.5}$ eV

DDeMarco, Blasi, AO ‘03

Systematic off-set



Thanks to D. Bergman

New Data

Challenge: to reach > 10^4 - 10^5 km^2 sr yr

Present experiments ~ 10^3 km^2 sr yr

AGASA (100 km^2 array scintillators)

exposure ~ 1.6 10^3 km^2 sr yr

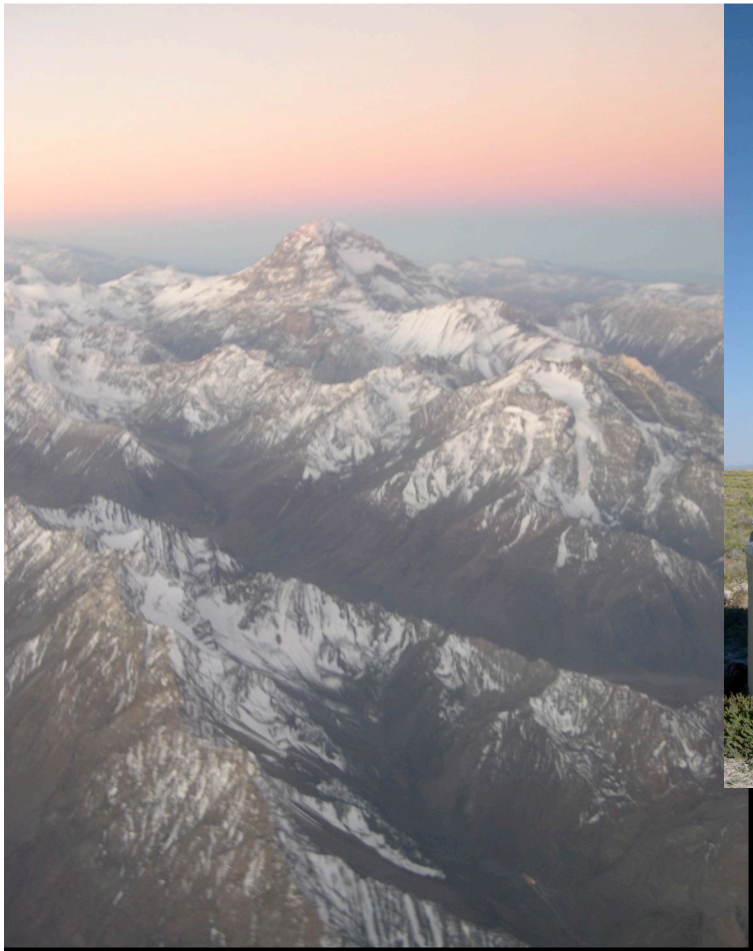
HiRes (Binocular Fluorescence Telescopes)

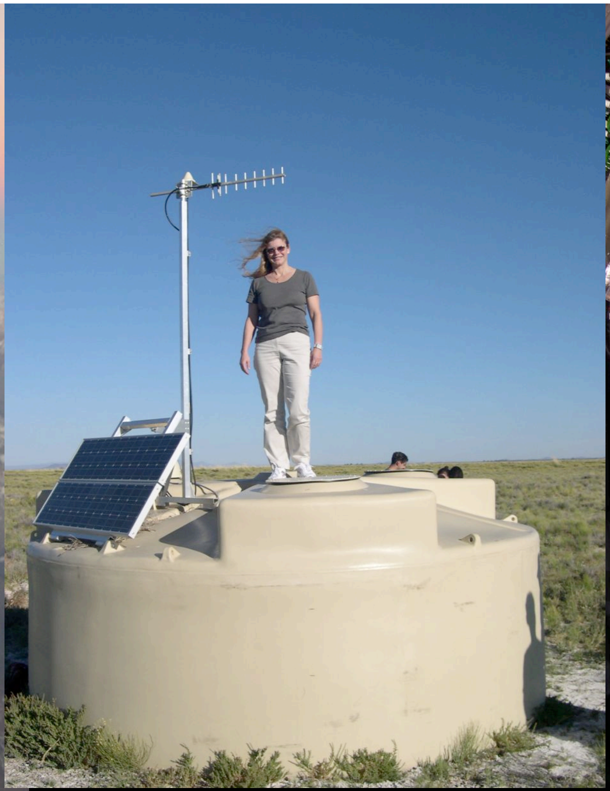
exposure ~ 2 10^3 km^2 sr yr

PIERRE AUGER Observatory (South)

3,000 km^2 array + 4 Fluorescence Telescopes

Aperture 6,600 km^2 sr - reach > 10^4 in 2 years





Pierre Auger Observatory

2 Giant AirShower Arrays: South – Argentina Funded, North – Not Yet

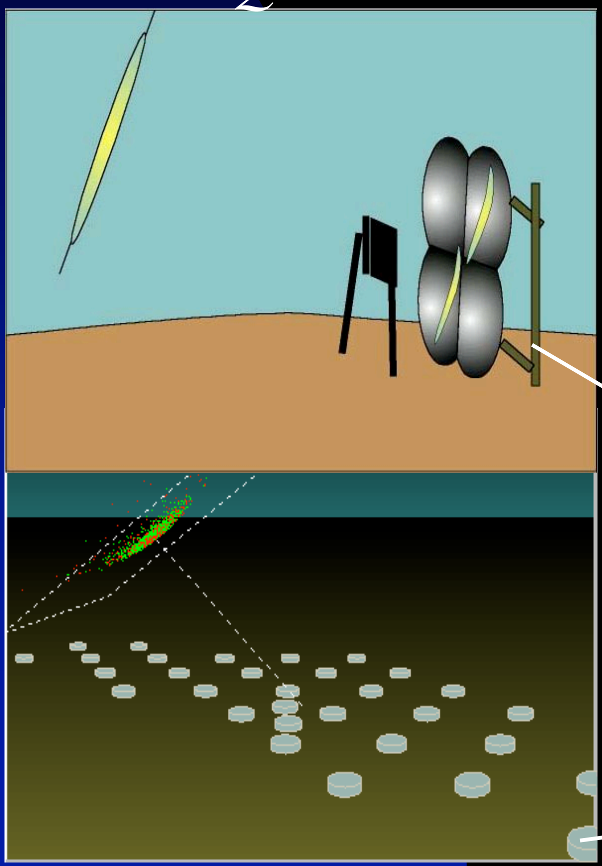
1600 particle detectors over 3000 km^2 + 4 Fluorescence Detectors
to Measure Direction, Energy, & Composition of
~ 60 events/yr E > 10^{20}eVand ~ 6000 events/yr E > 10^{19}eV

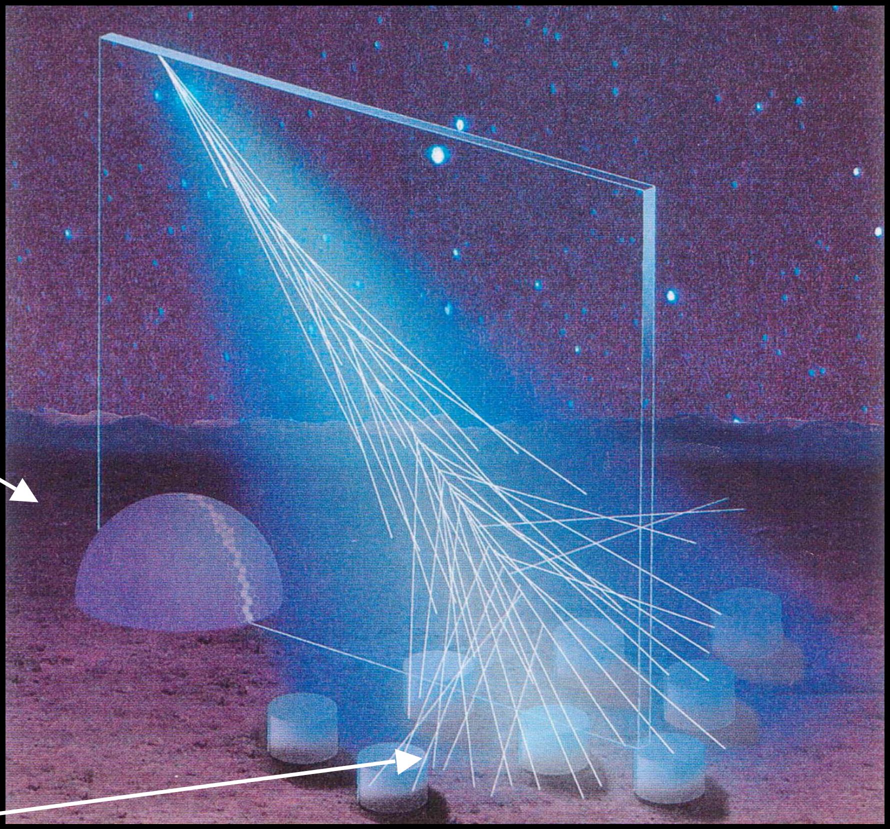
> 250 scientists from 16 countries

Pierre Auger Project

2 Giant Ground Array (30 x AGASA) with Fluorescence Detectors
HYBRID DETECTOR - use both techniques

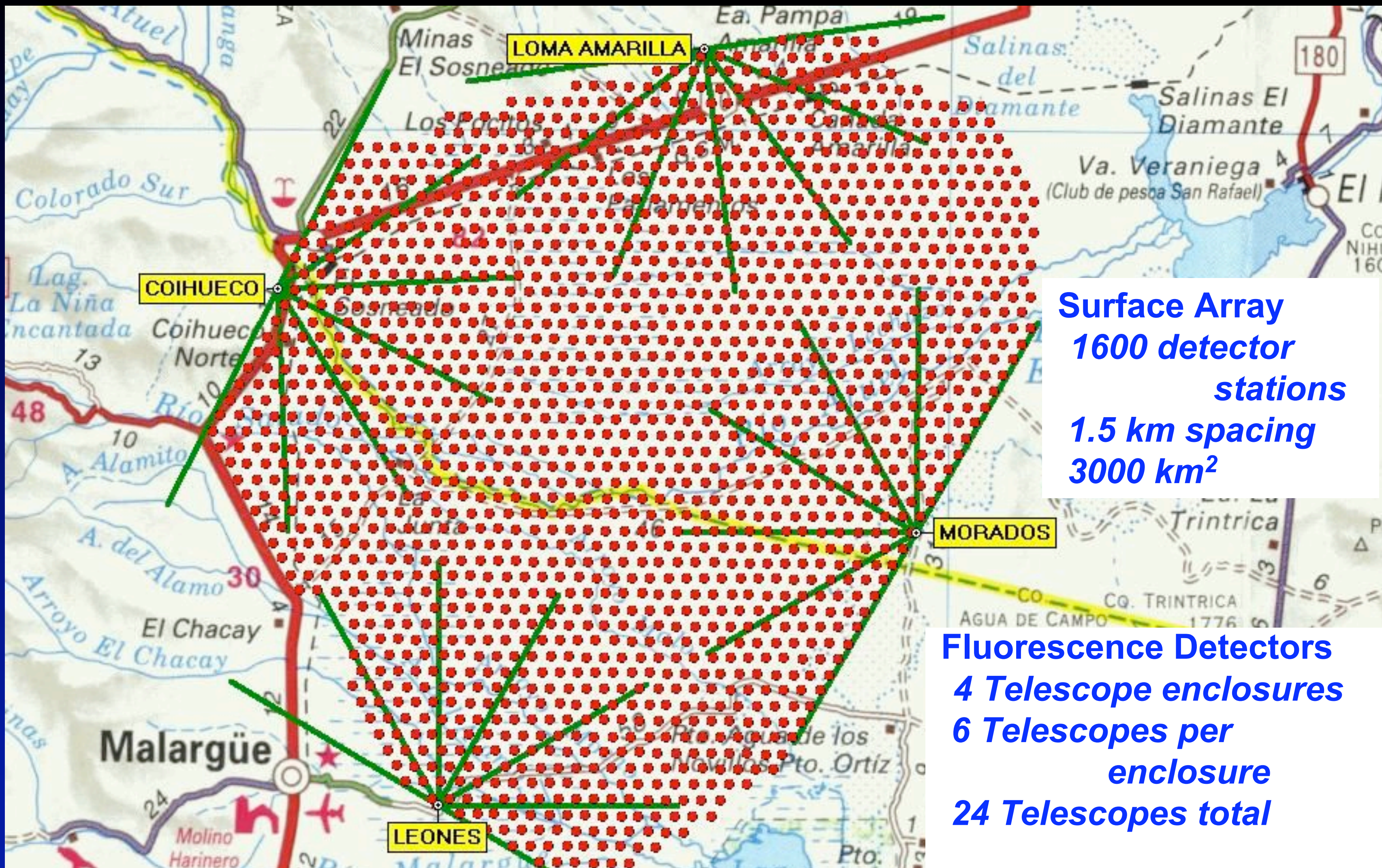
HIGH QUALITY





LARGE QUANTITY

The Observatory Plan



Surface Array

1600 detector stations

1.5 km spacing

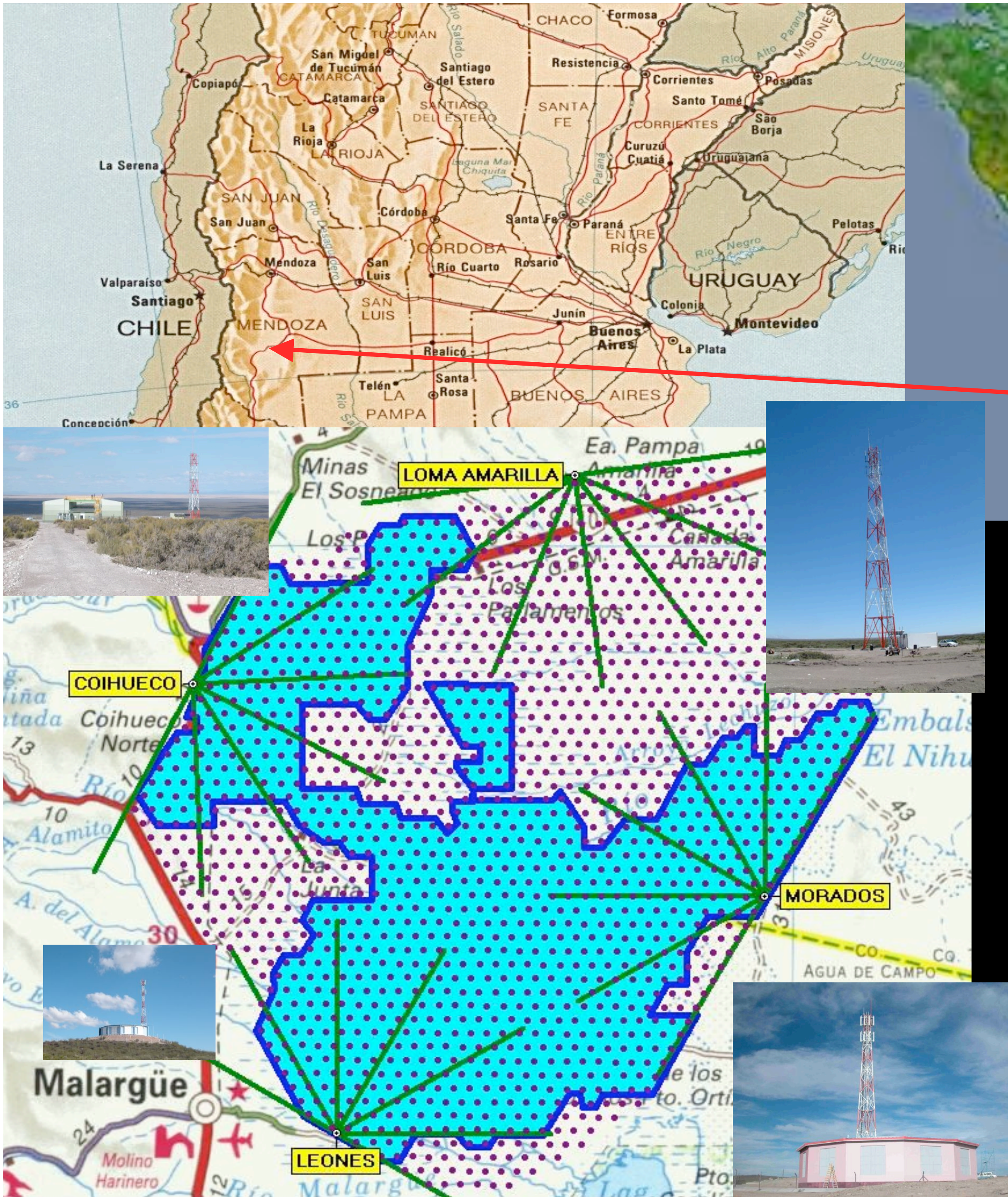
3000 km^2

Fluorescence Detectors

4 Telescope enclosures

6 Telescopes per enclosure

24 Telescopes total



Auger South

Construction

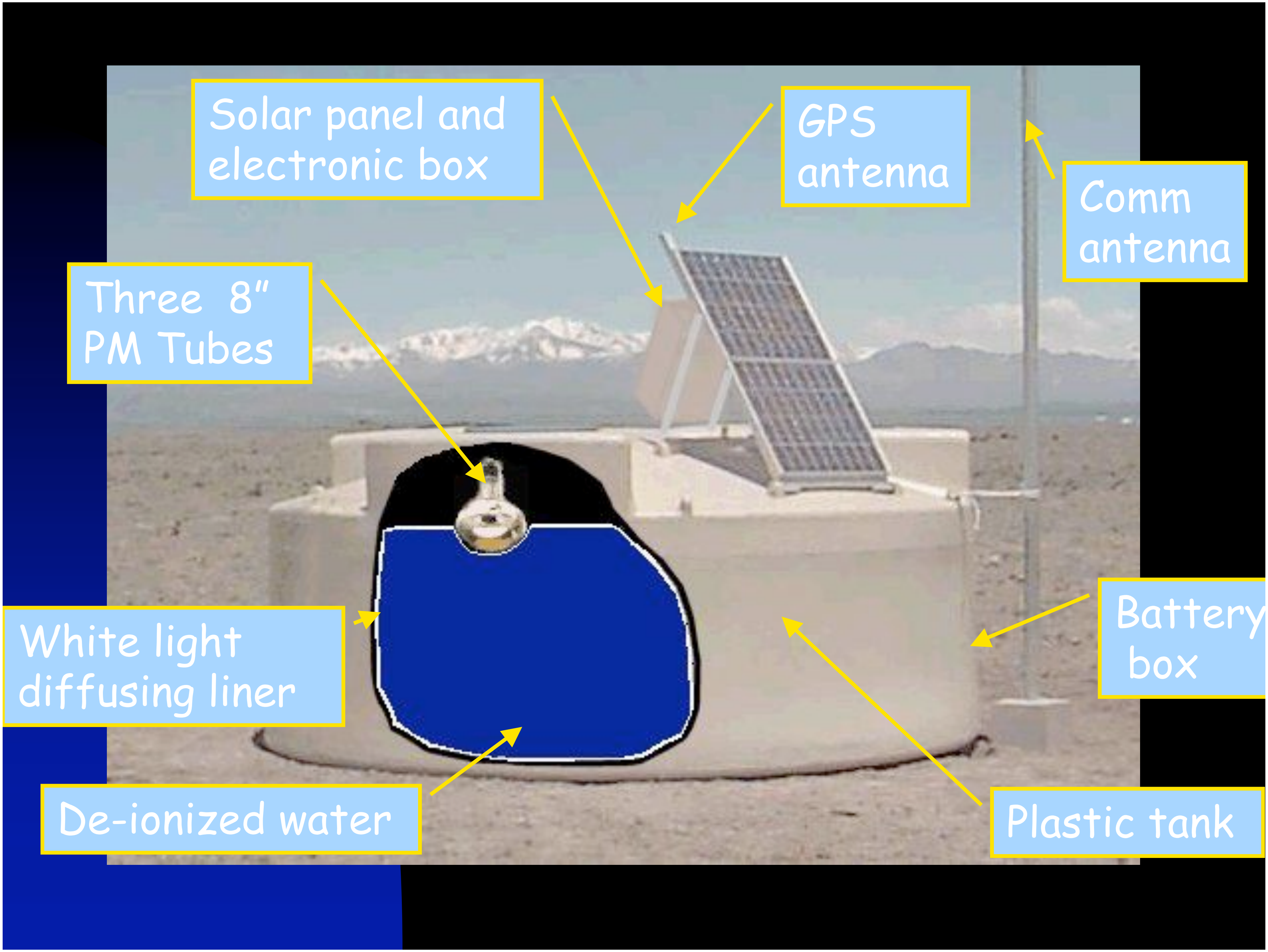
> 1000 surface detector stations deployed

(~900 with electronics and sending triggers)

Three fluorescence buildings complete each with 6 telescopes


tanks aligned seen from Los Leones
(test your eyes)

tanks aligned seen from Los Leones (zoomed)

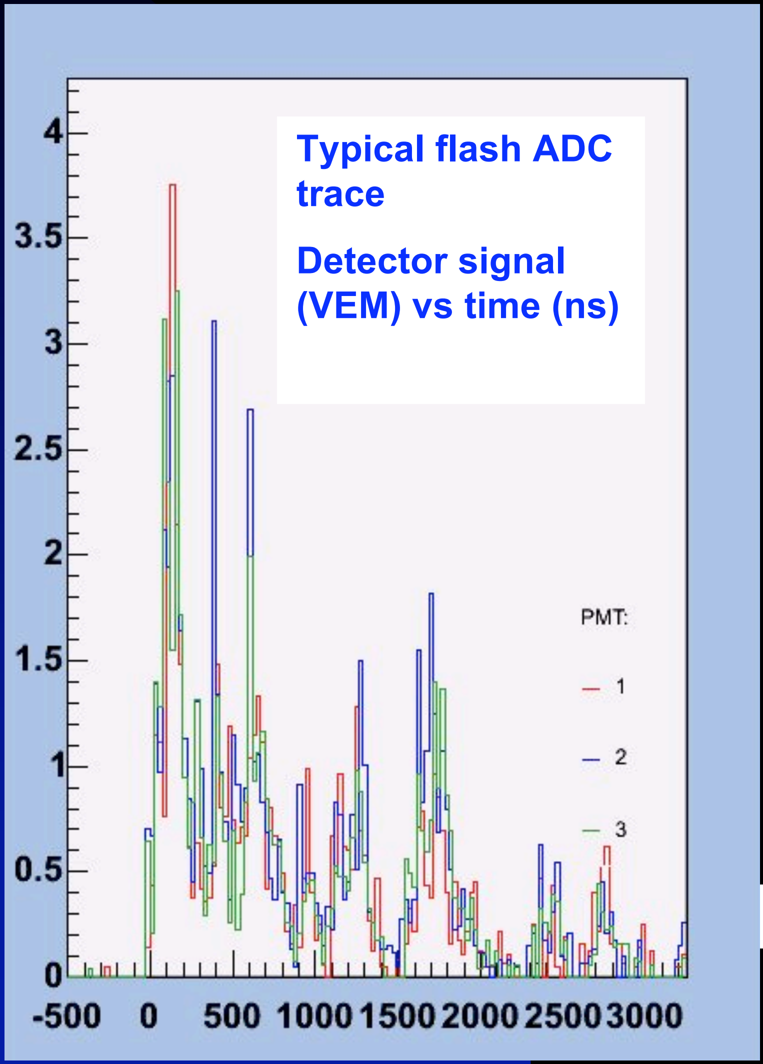


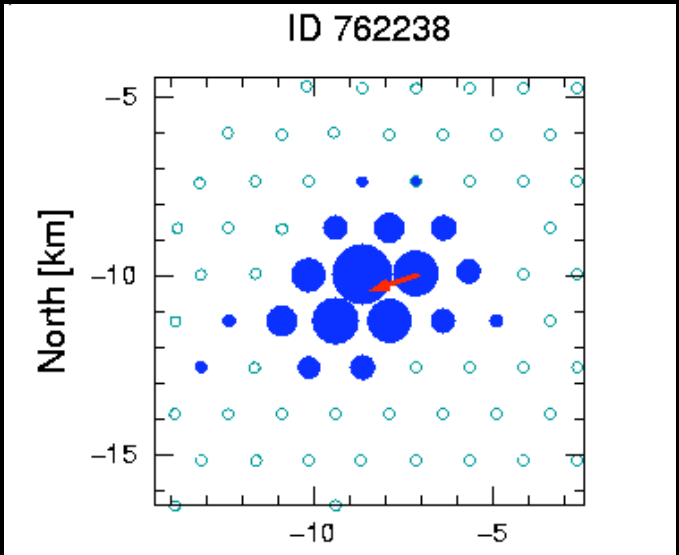
Solar panel and electronic box
GPS antenna
Comm antenna
Three 8" PM Tubes
White light diffusing liner
Battery box
De-ionized water
Plastic tank

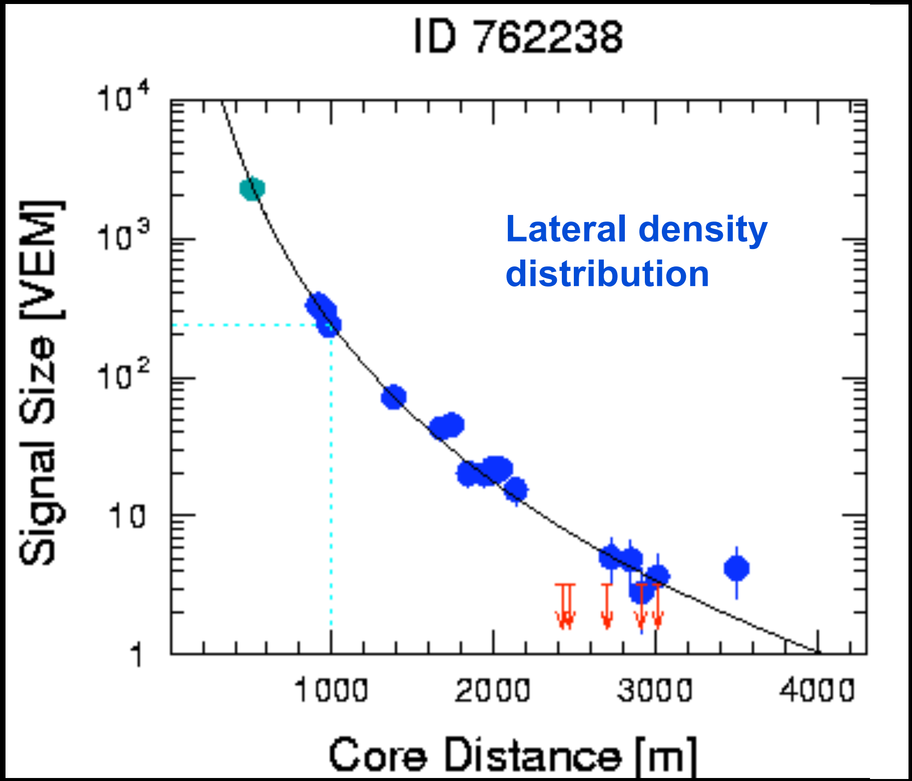
Example Event 1

A moderate angle event 762238

Zenith angle ~ 48º, Energy ~ 70 EeV



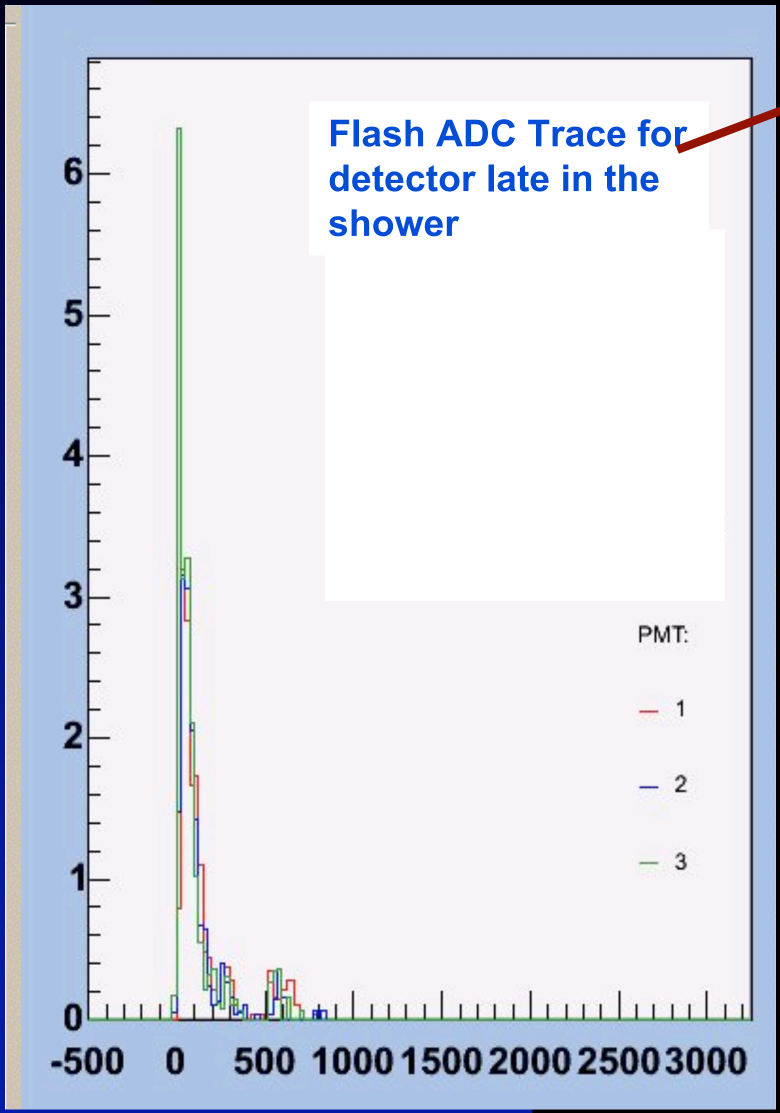


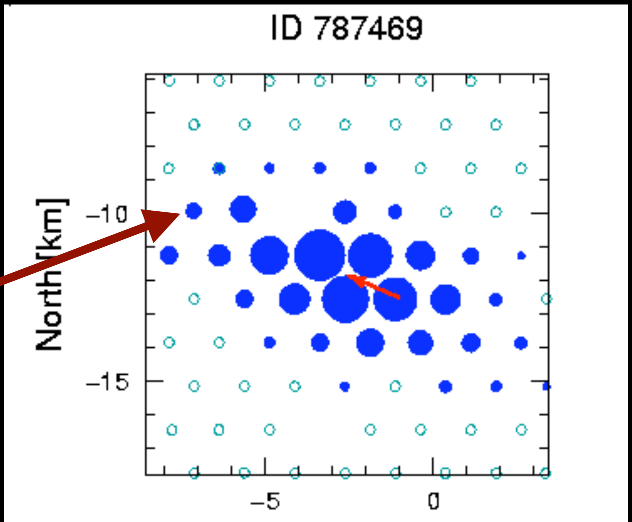


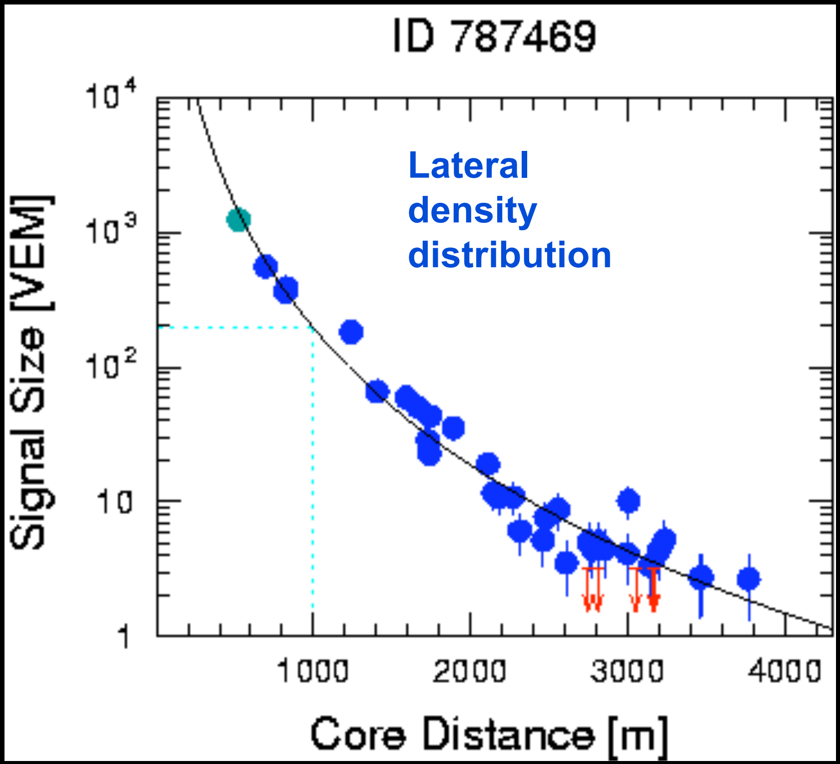
Example Event 2

A high zenith angle event - 787469

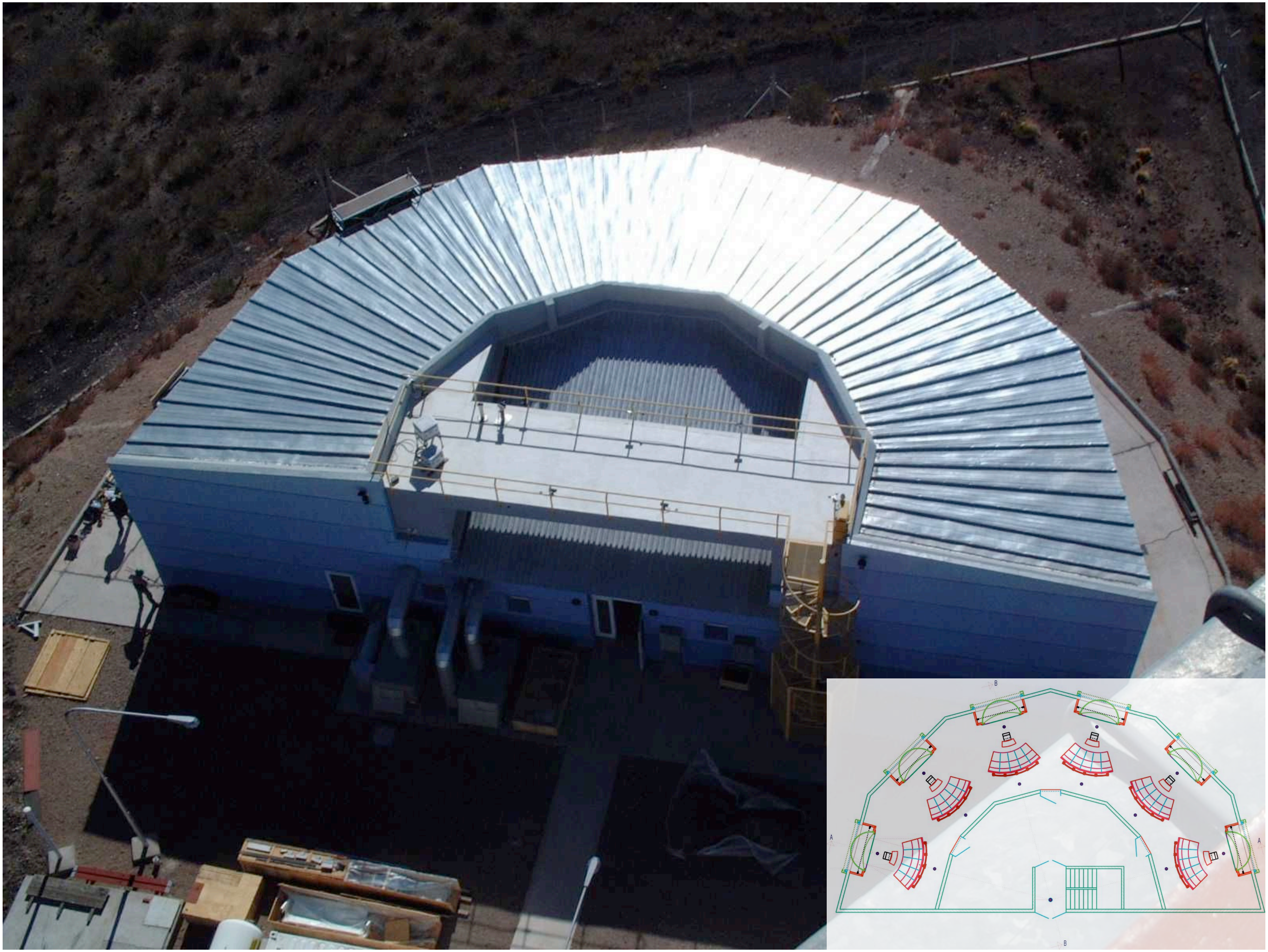
Zenith angle ~ 60º, Energy ~ 86 EeV

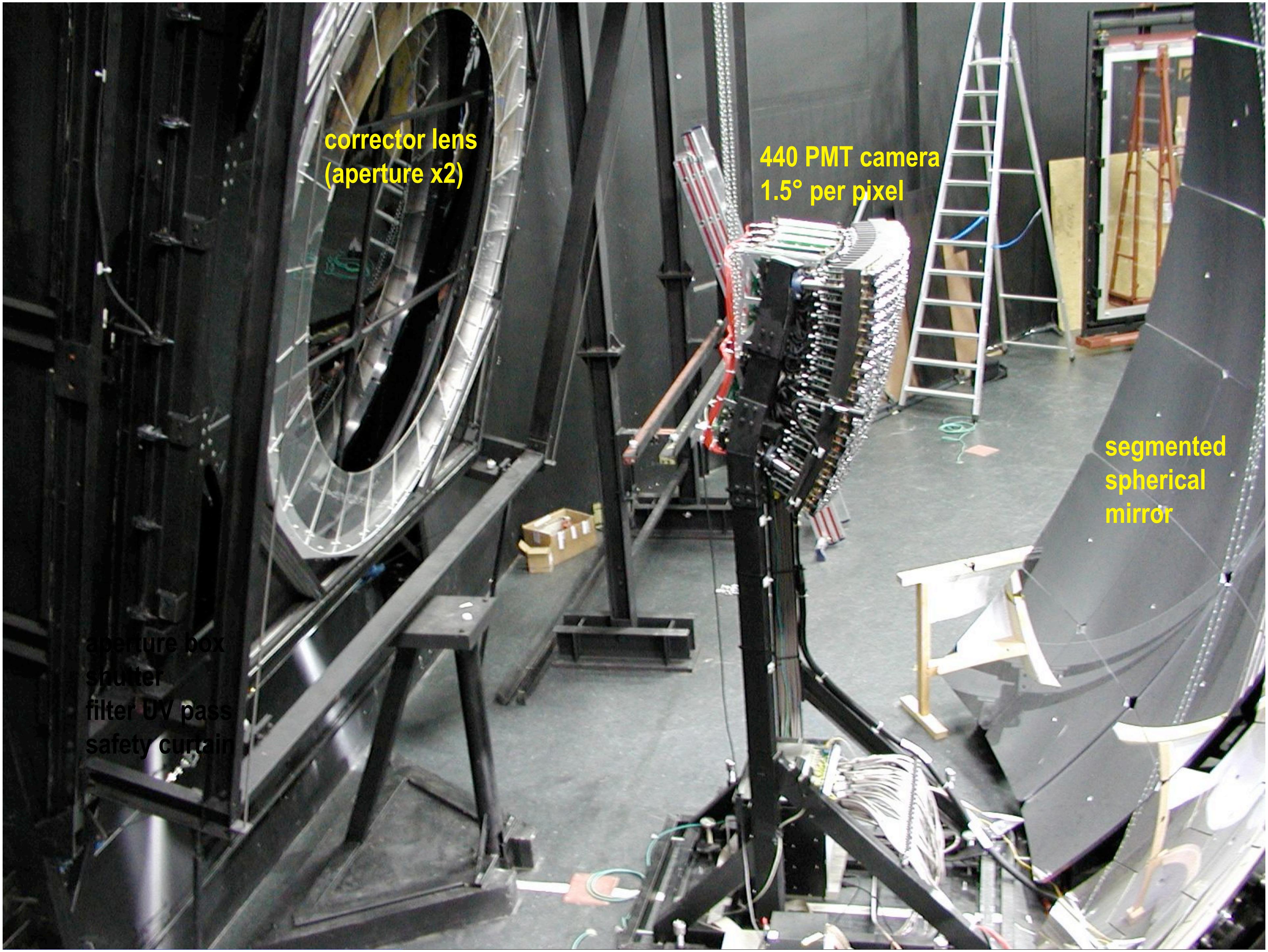






view of Los Leones Fluorescence


B
A
A
B


corrector lens
(aperture x2)
440 PMT camera
1.5° per pixel
segmented
spherical
mirror
aperture box
shutter
filter UV pass
safety curtain

Atmospheric Monitoring & Fluorescence Detector Calibration

Atmospheric Monitoring

Central Laser Facility (laser optically linked to adjacent surface detector tank)

- **Atmospheric monitoring**
- **Calibration checks**
- **Timing checks**

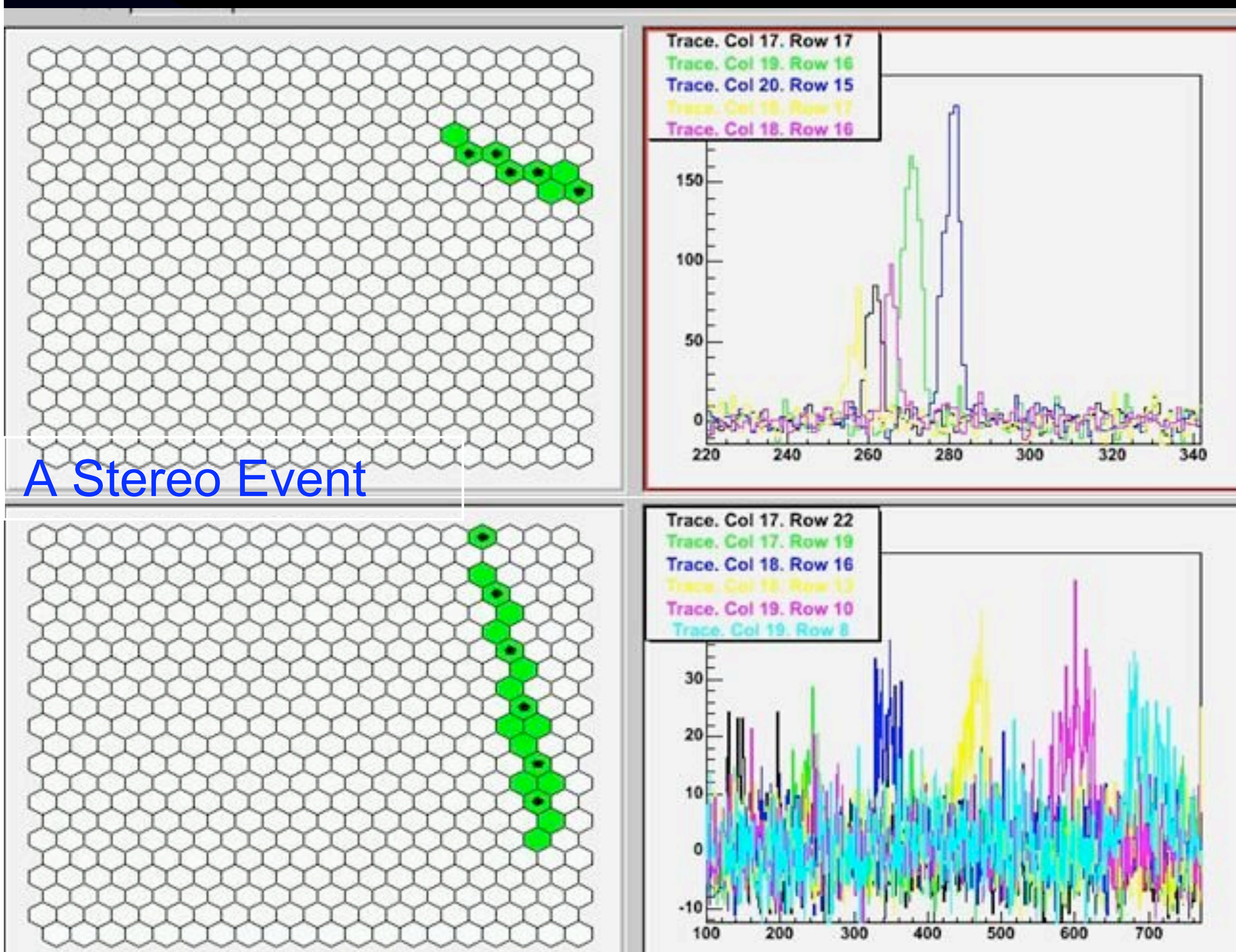
Radiosondes for atm profile

Lidar at each fluorescence eye for atmospheric profiling - "shooting the shower"

Absolute Calibration

Drum for uniform illumination of each fluorescence camera

FD Stereo Event



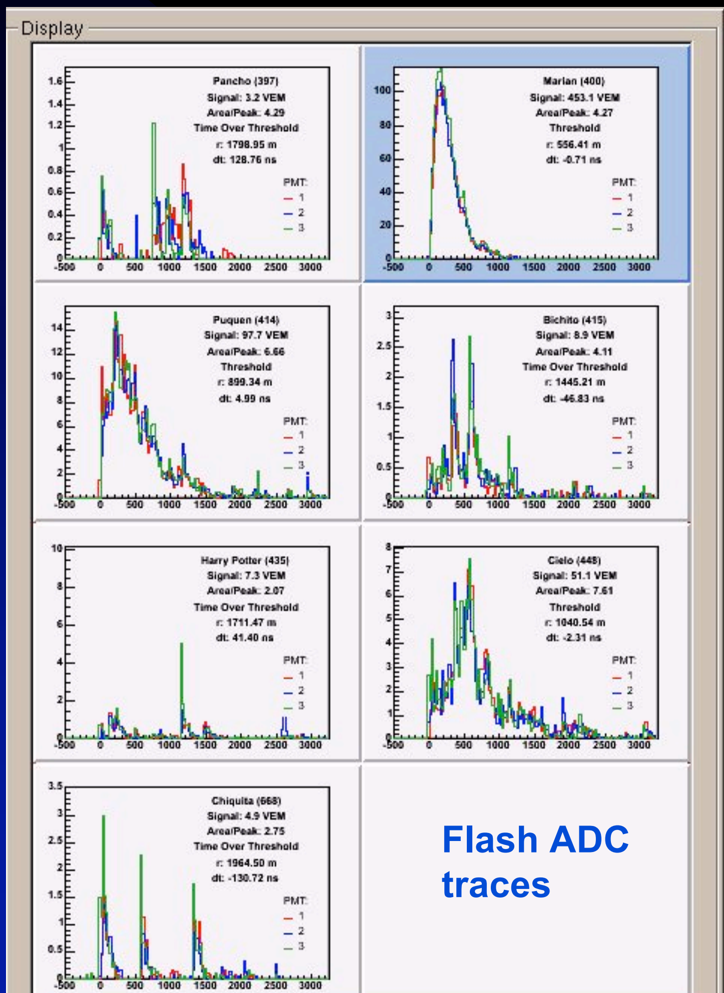
100ns time bin

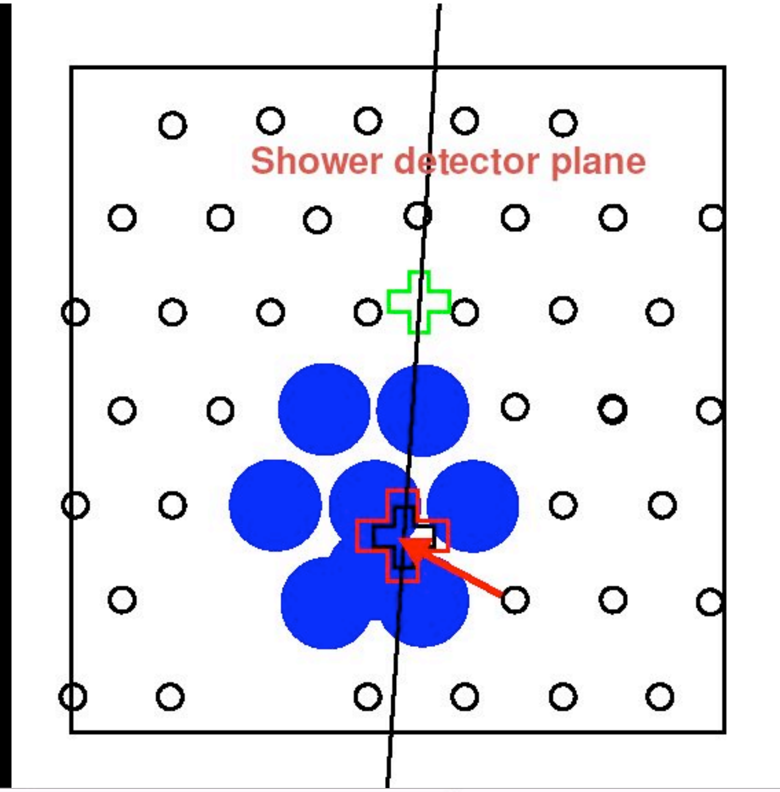
- Threshold trigger on individual pixels -
- “tracks” 1 Hz trigger rate per 6 cameras
- Multi-camera events merged within 2 sec
- Geometry recon in 5 sec, passed to central data acquisition system
- Induces SD readout of tanks within range.
- Obtain **“Hybrid Events”** with both longitudinal and transverse shower information.

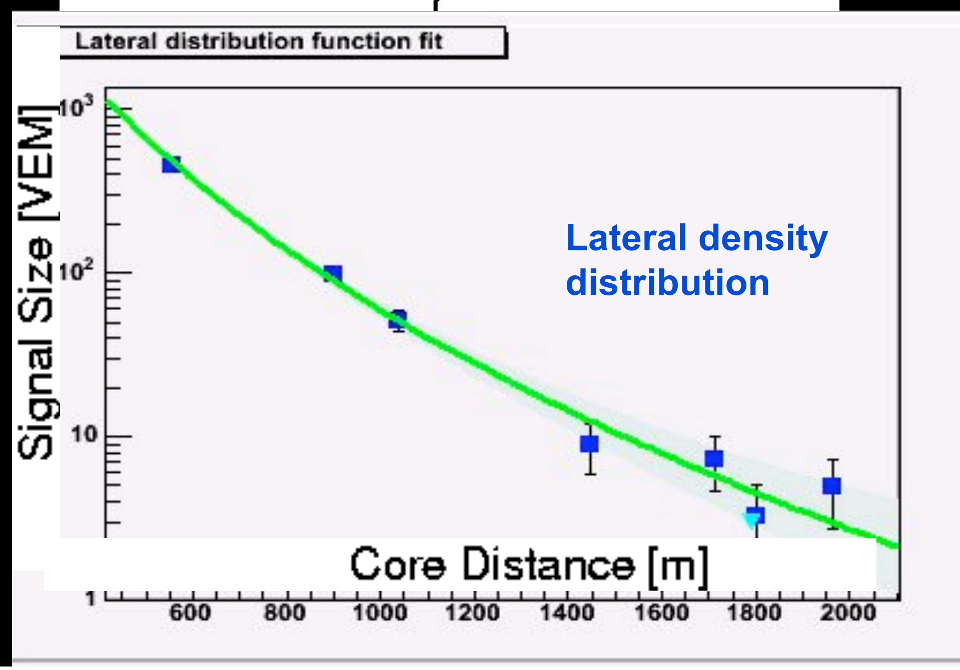
Example Event 3

A hybrid event – 1021302

Zenith angle ~ 30º, Energy ~ 10 EeV



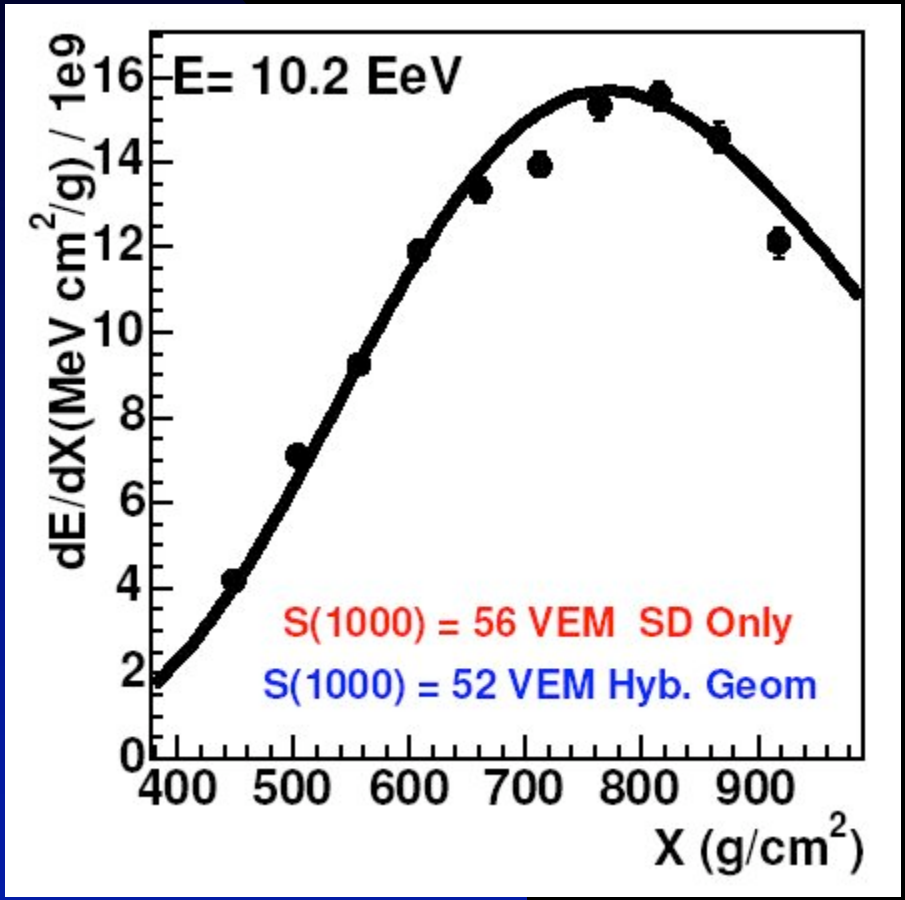


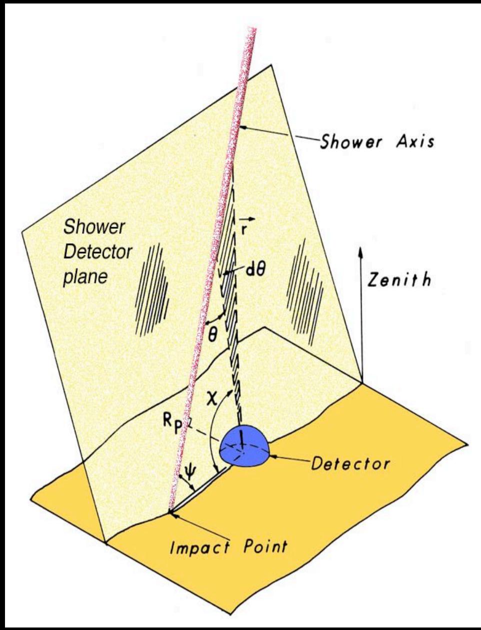


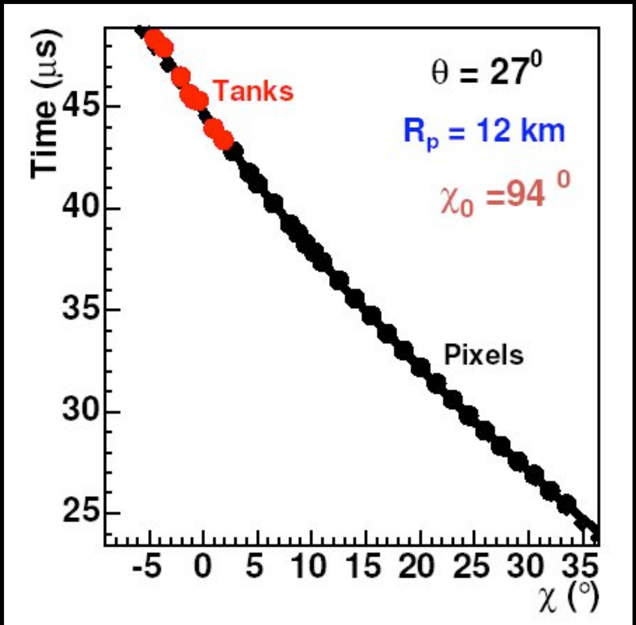
Example Event 3

A hybrid event – 1021302

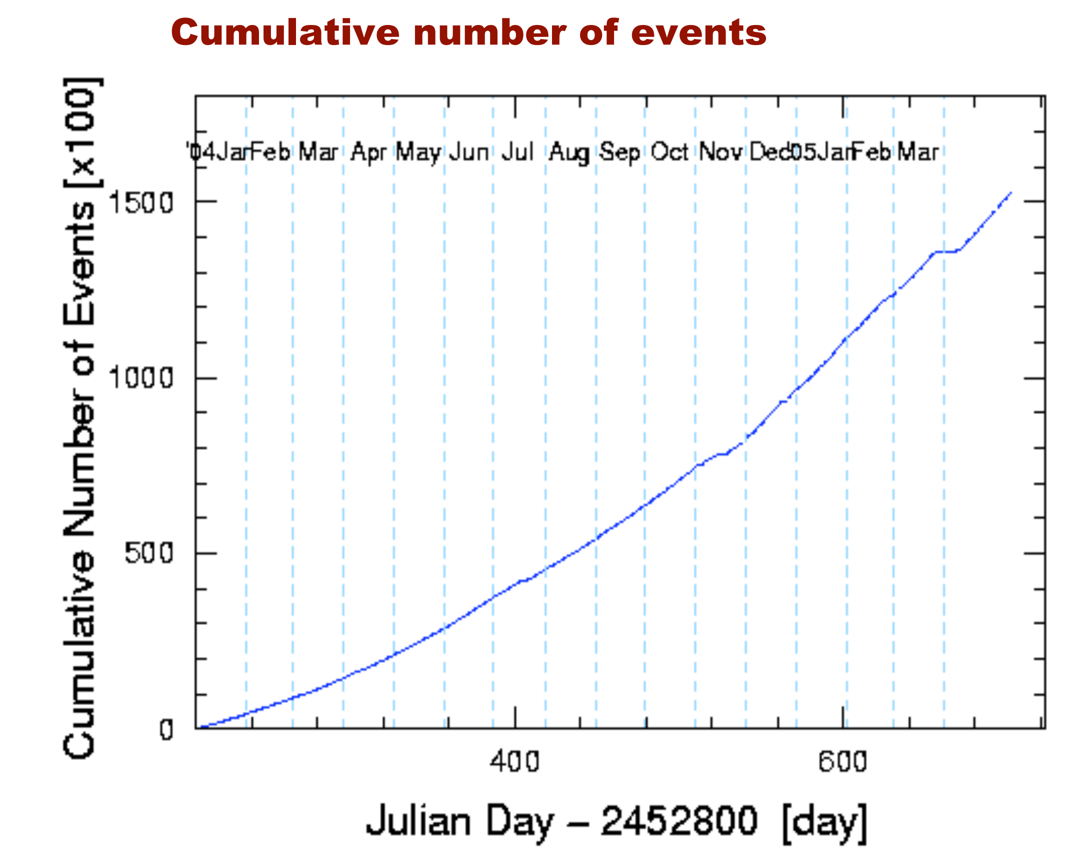
Zenith angle ~ 30º, Energy ~ 10 EeV







First Auger Data Set



Collection period –

1 Jan 2004 to 5 June 2005

Zenith angles - 0 - 60º

Current rate - 18,000 / month

Total - 150,000

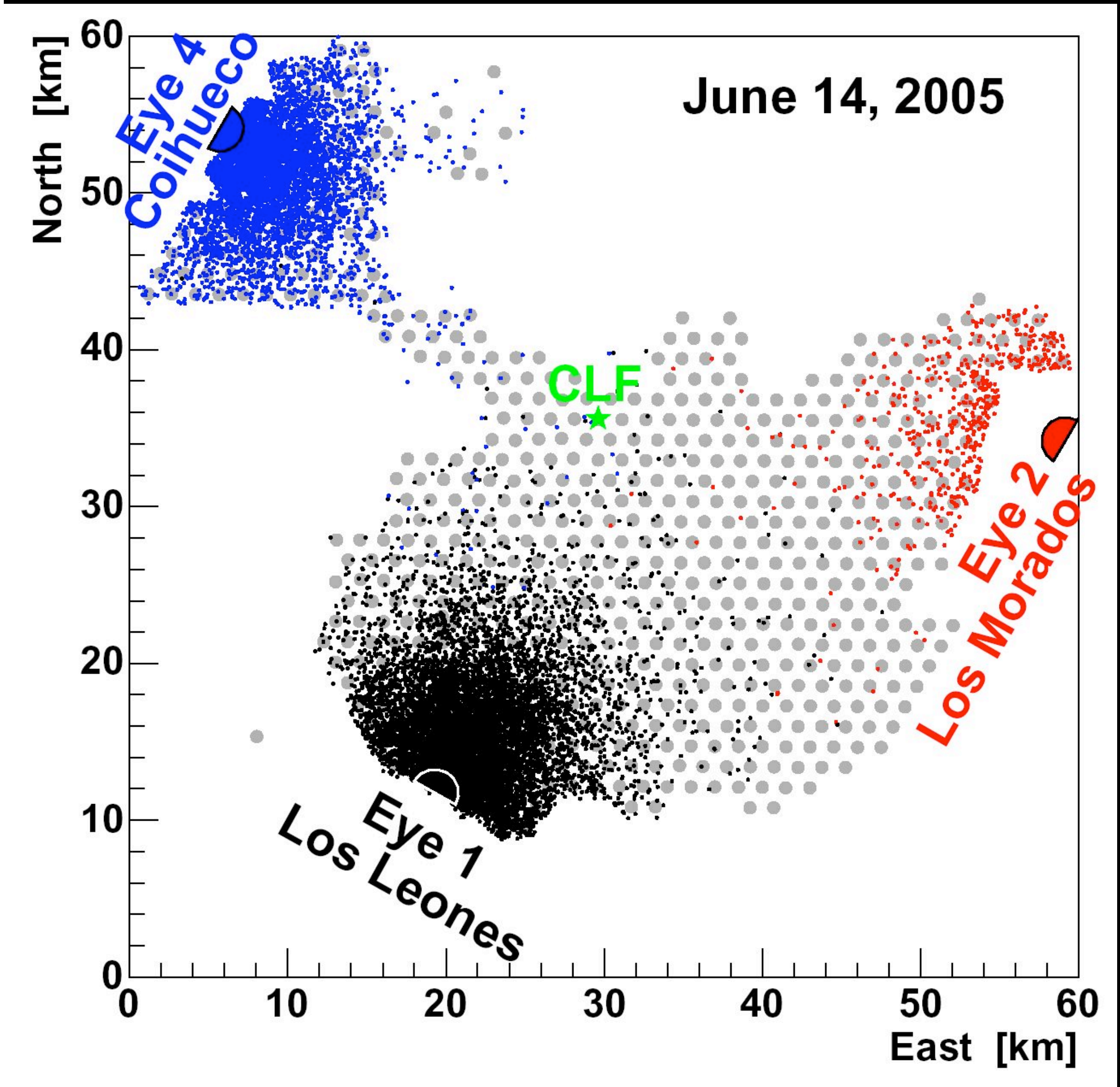
Surface array events

(after quality cuts)

Total Exposure 1750 km^2 sr yr

(~ 1.07 * AGASA)

Hybrid Events



Reconstructed

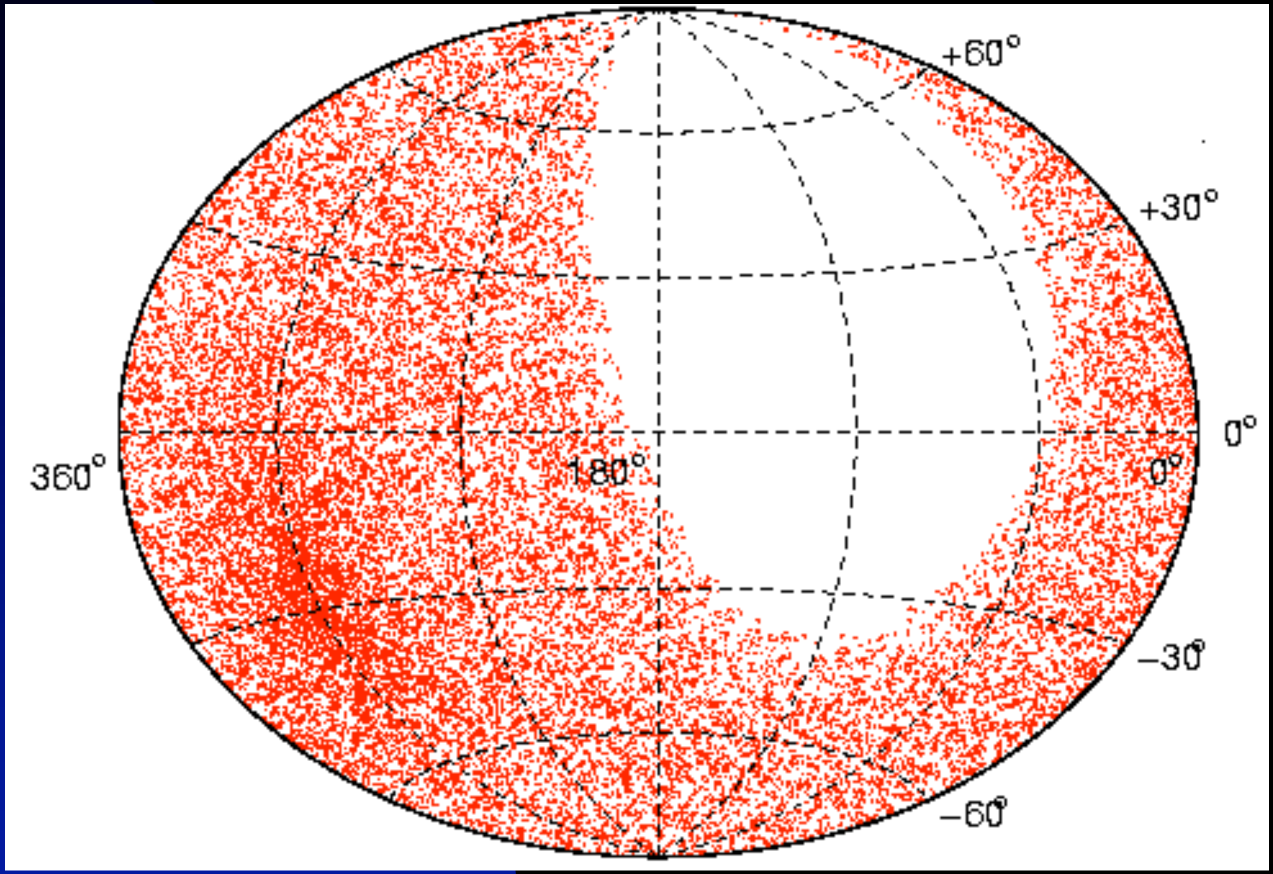
1,800/month

Total = 10,000

Mostly at low energies near eyes

~ 2000 (>1 EeV)

Sky Map of Data set



Auger latitude= -36.

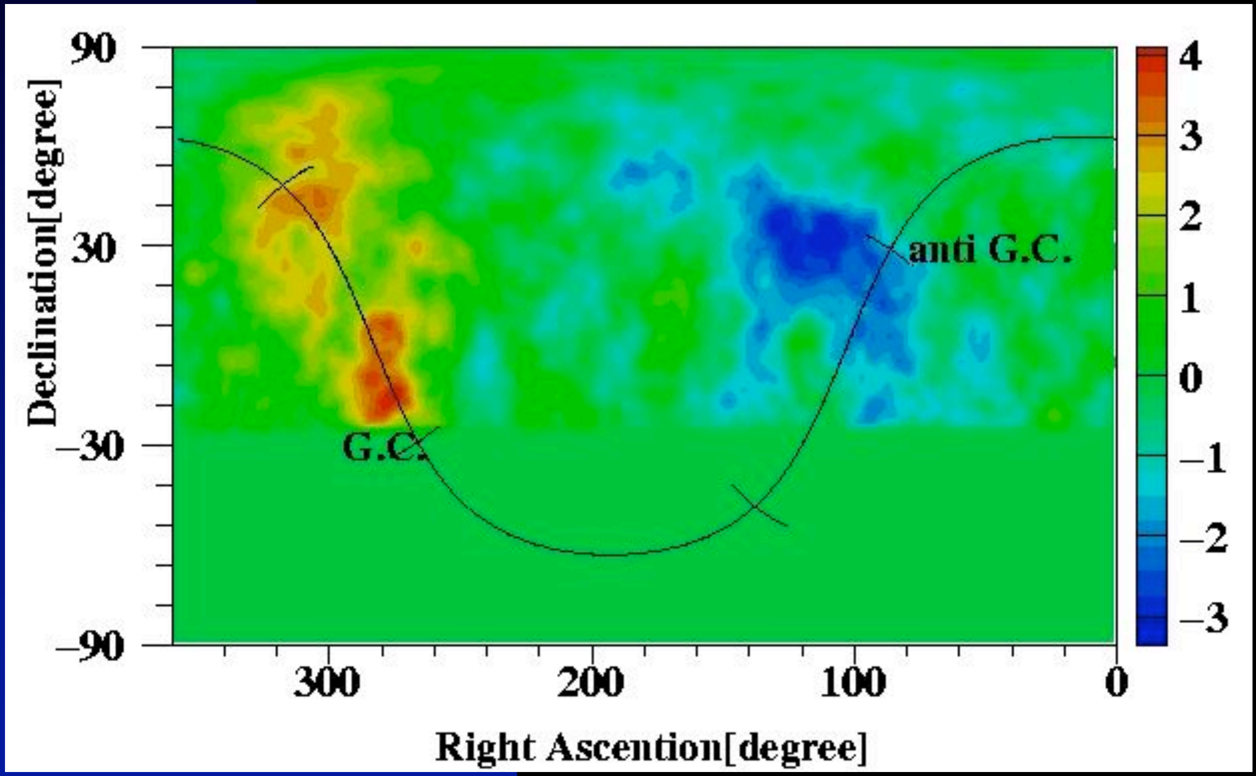
Always looking towards South.

Limited coverage in Northern region.

Mainly measure properties of the Southern sky flux!

Previous Observations of the Galactic Center

AGASA



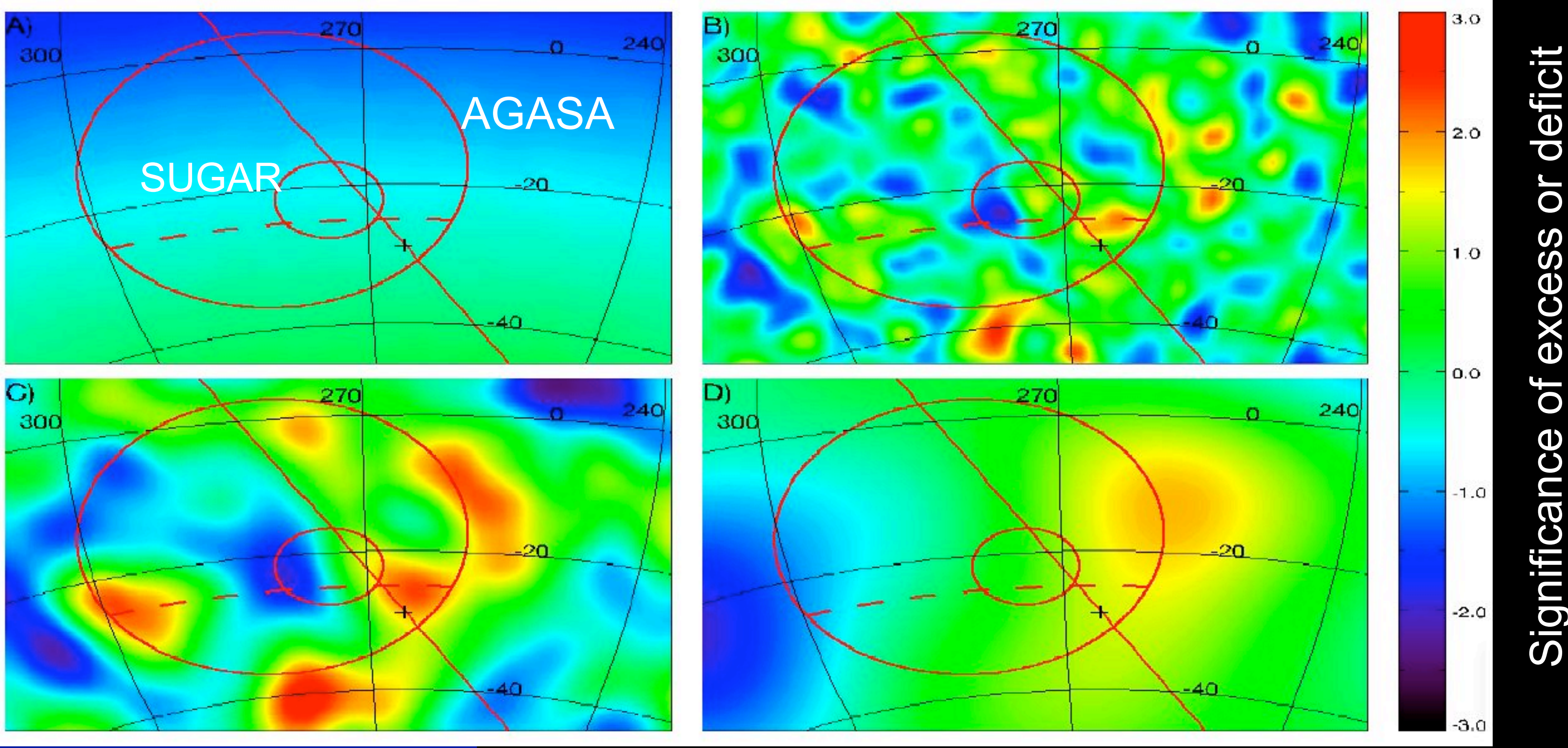
AGASA -
22% excess at 4.5
20 degree window
near the GC with
E=1-2.5EeV.

SUGAR -
a 2.9σ excess with
5.5 degree window
near the GC with
E=0.8-3.2EeV.

Auger: No excess seen in either region

Our coverage map by shuffling event zenith, day, hour

Events smoothed with true resolution, Energy = 0.8-3.2 EeV



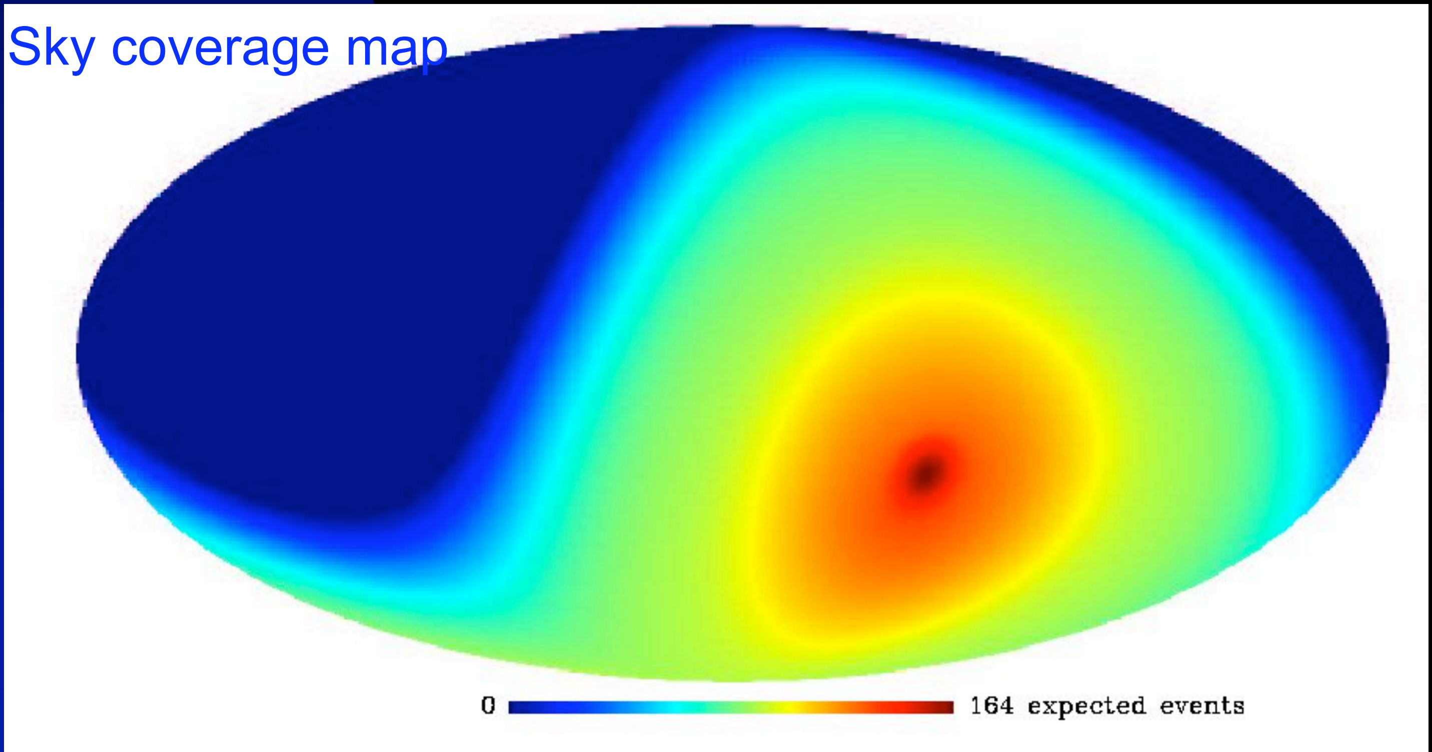
Smoothed at SUGAR scale, SUGAR energy window

Smoothed at AGASA scale, AGASA energy window

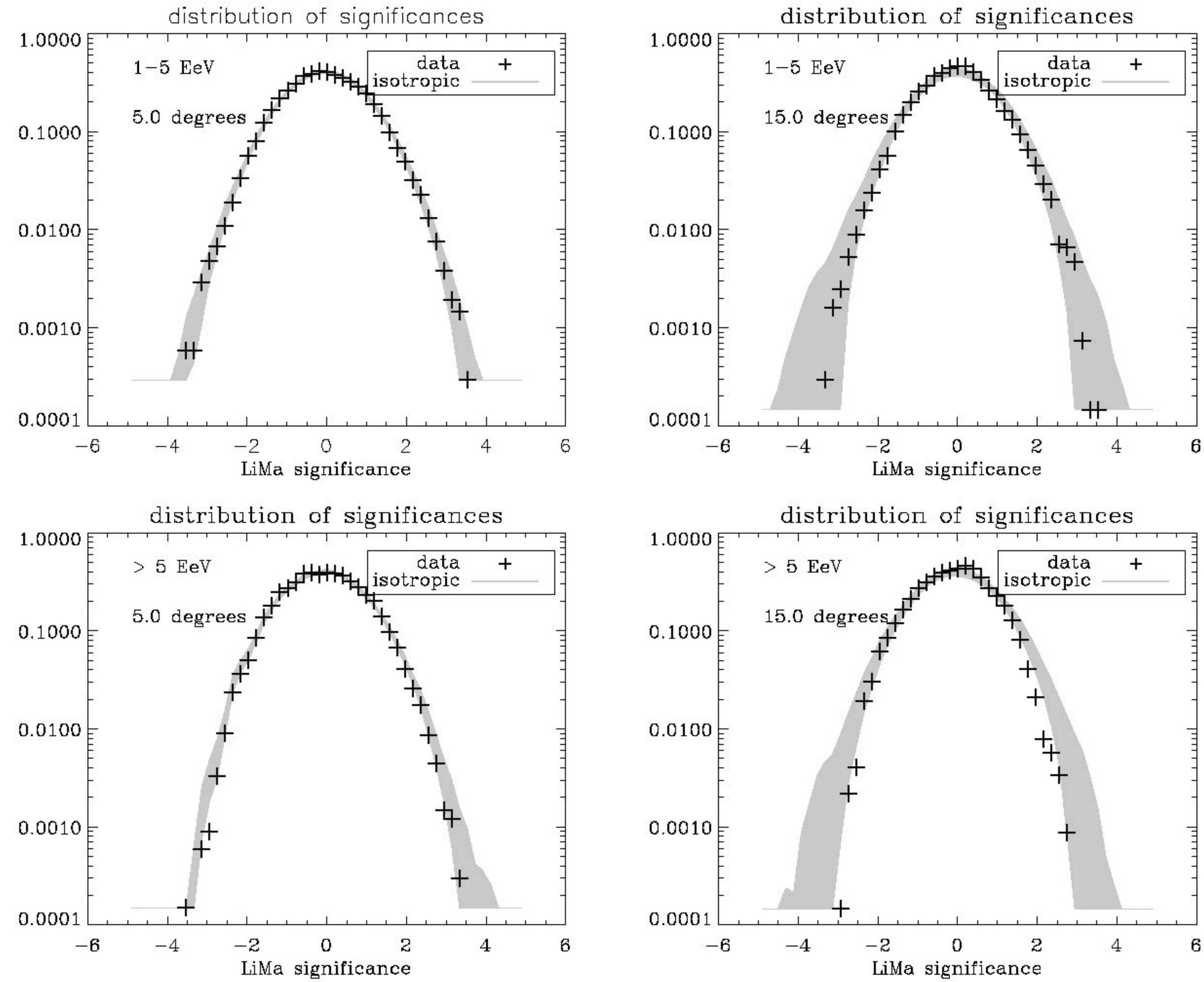
Search for localized excesses

Predefined search parameters:

- E=1-5 EeV, or E>5 EeV
- Angular scale=5 degrees, or 15 degrees (tophat)
- Uses Monte Carlo energy converter instead of CIC (for now)



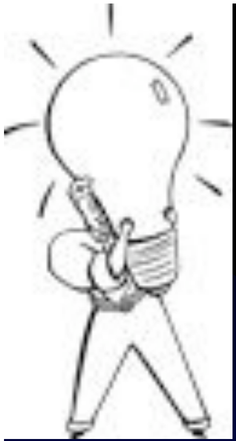
Data is consistent with isotropy



Other pre-defined targets not seen either.

Target	$\ell(^\circ)$	$b(^\circ)$	Radius	$\log(E/\mathrm{EeV})$	Found	Exp.	Prob	Req. Prob
GC 1	0.00	0.00	15°	$\geqslant 18$	155	167.3	-	0.0035
GC 2	0.00	0.00	Point (2°)	$18 - 18.5$	2	2.5	-	0.00025
AGASA SUGAR	7.00	0.00	Point (2°)	$18 - 18.5$	3	2.69	0.43	0.00025
NGC0253	88.92	-87.80	5°	$\geqslant 19.5$	0	0.01	-	0.00005
NGC3256	277.56	11.49	5°	$\geqslant 19.5$	0	0.01	-	0.00005
Centaurus A	309.43	19.44	5°	$\geqslant 19.5$	0	0.01	-	0.00005

NO SIGNIFICANT ANISOTROPIES SO FAR



The Auger Model-Independent Spectrum Approach

Use the strengths from each technique:
FD(Hybrid) energy, SD statistics, SD exposure.

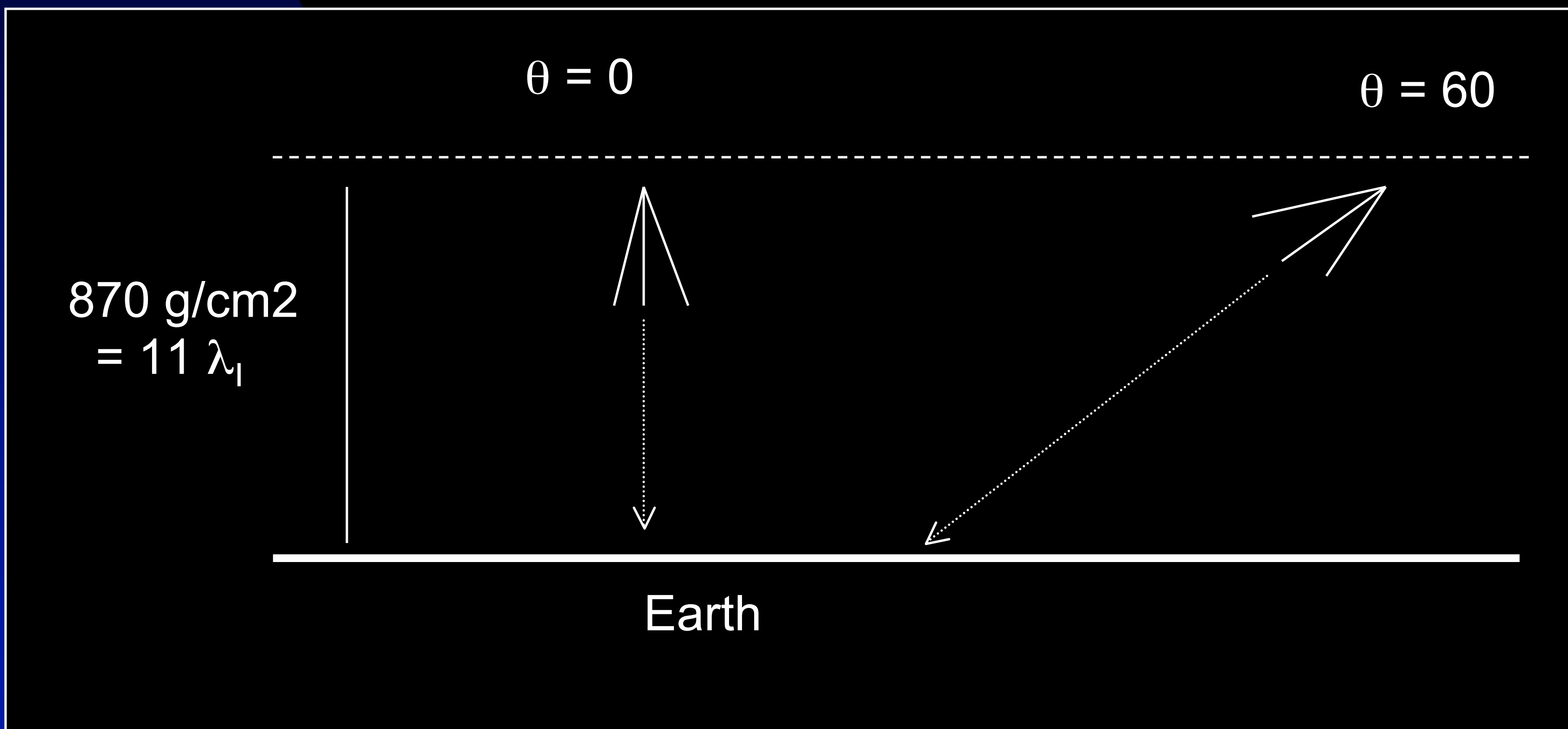
SD data → ground parameter S(1000) = SD signal at 1000m

Determine the S(1000)→ Energy & Zenith Angle conversion
   Zenith Angle dependence uses CIC: SD and Hybrid data
   FD energy scale Normalization via Hybrids

+ SD exposure → measured spectrum.

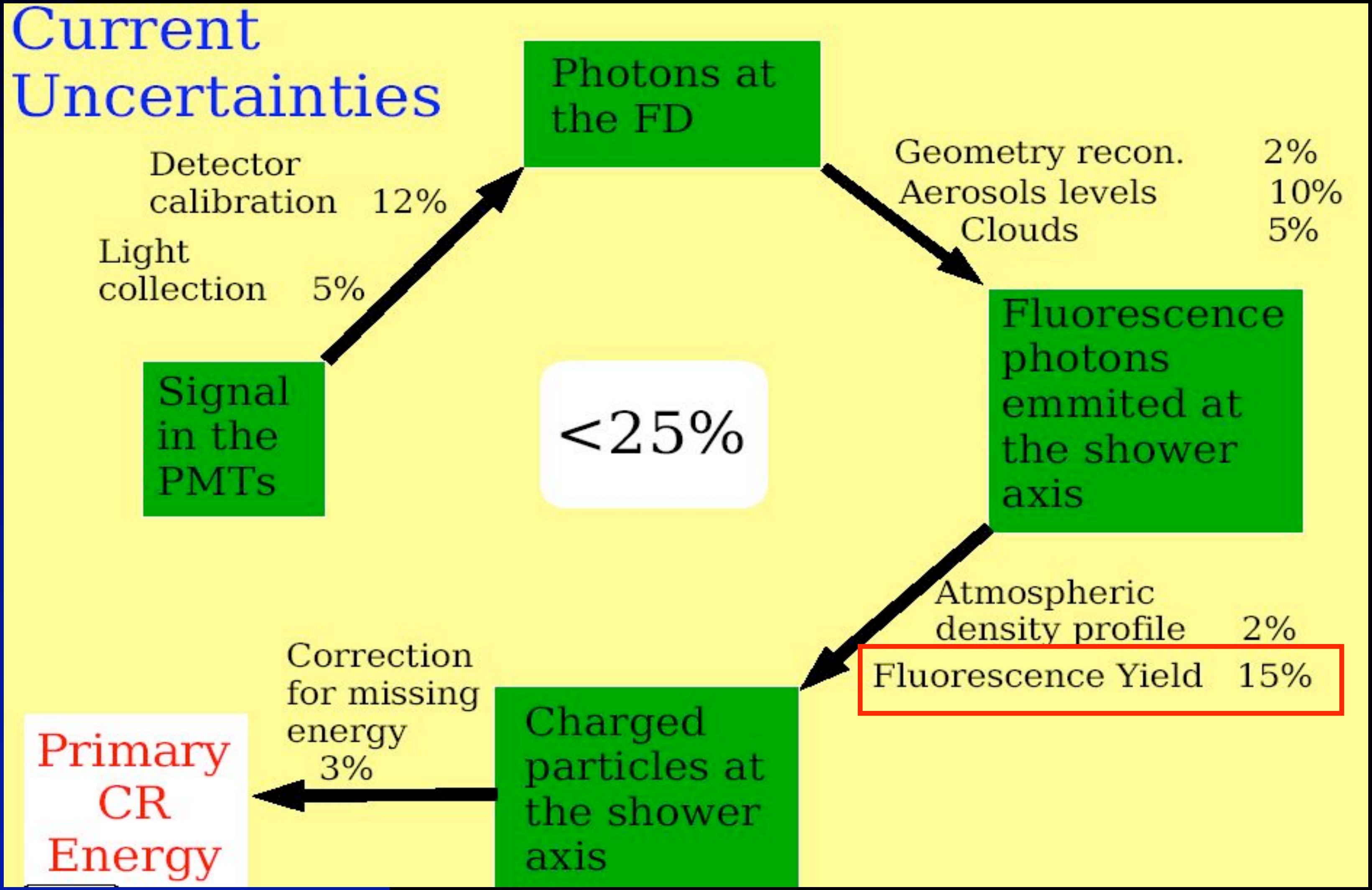
Each step is empirically determined!

Flux attenuation in the atmosphere is θ dependent

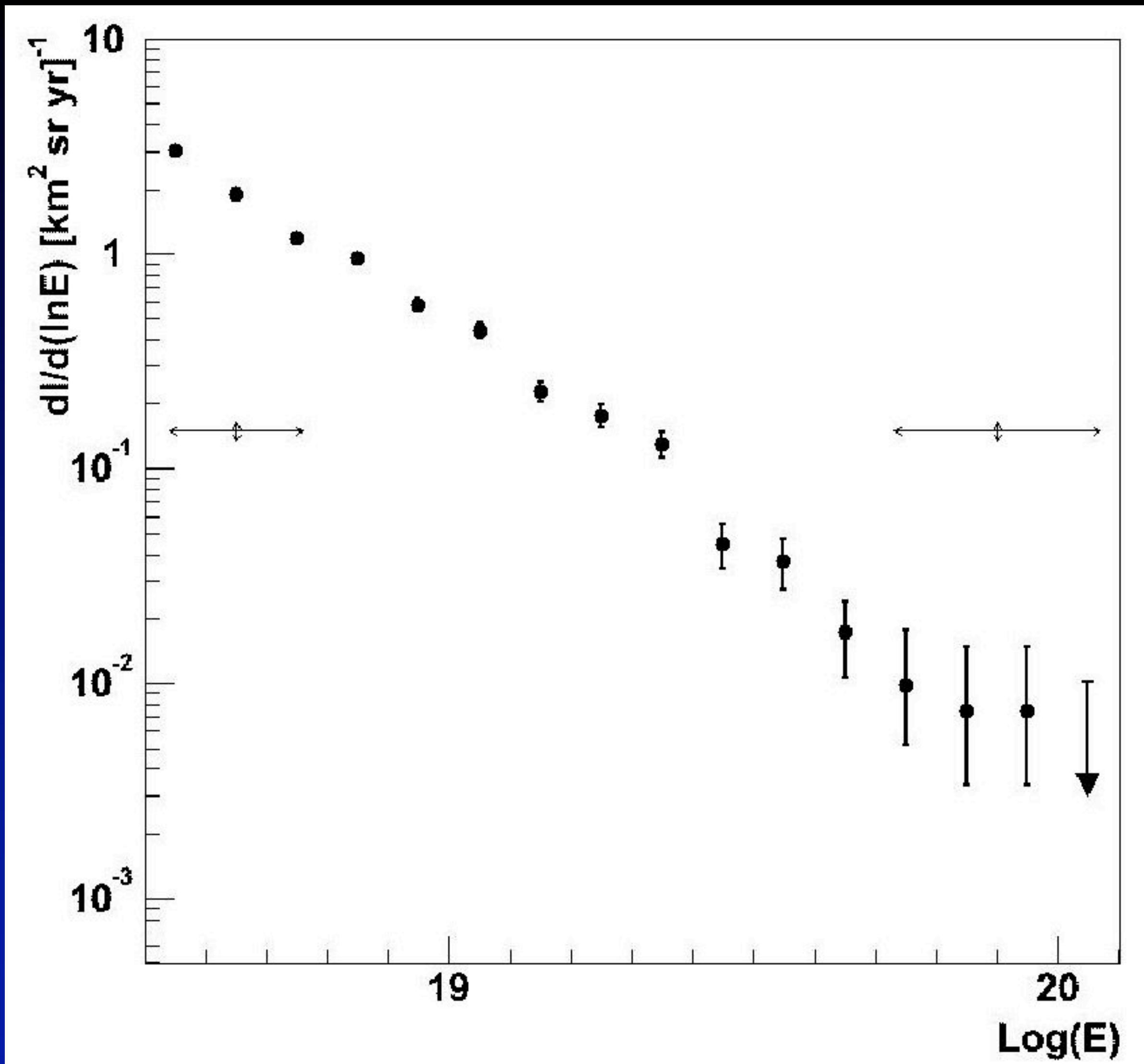


The "slant depth" is 870g/cm2 * sec(θ)

Systematic Errors in the FD (Hybrid) Energy Normalization



First Auger South Energy Spectrum



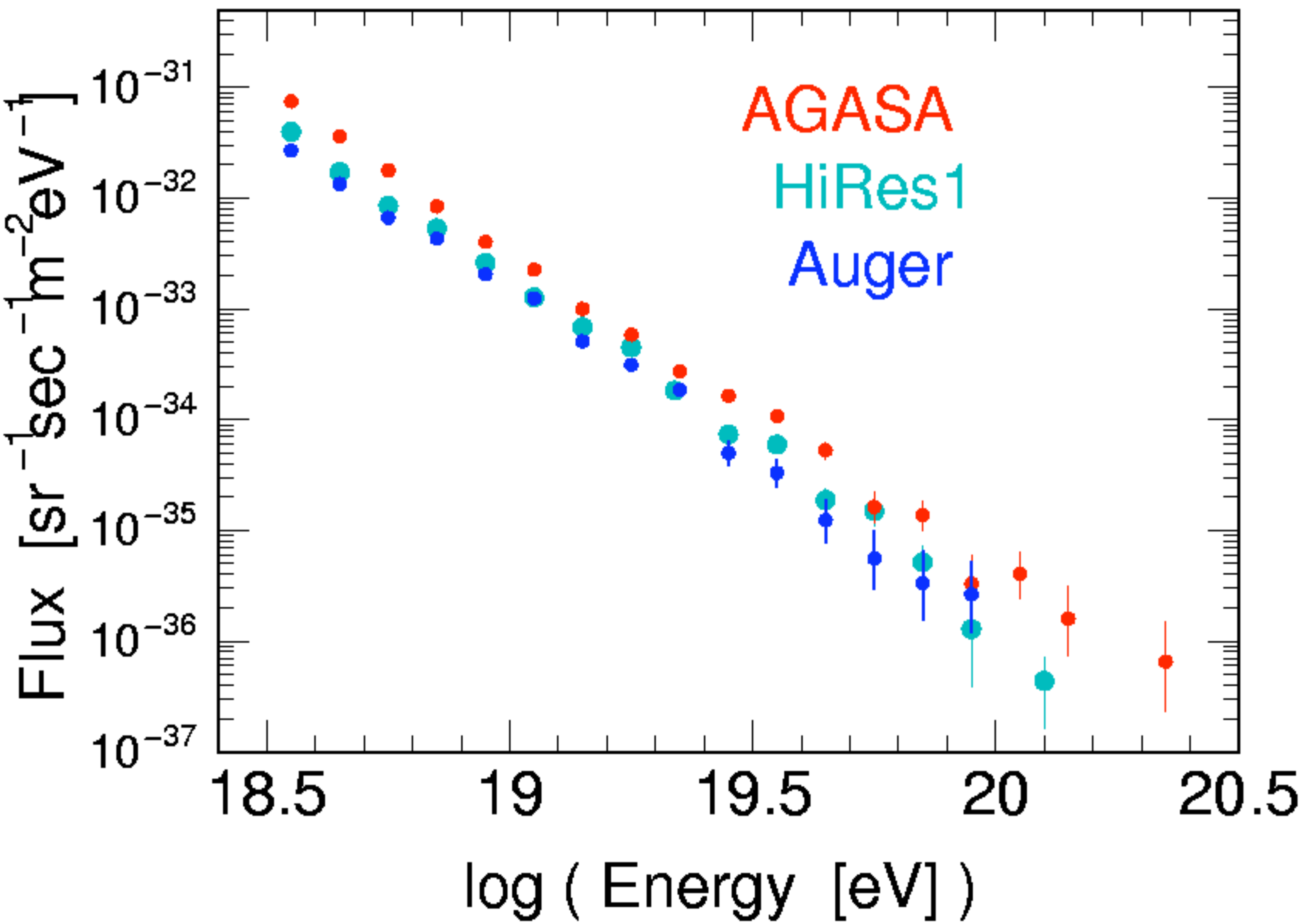
dN/d(lnE) = E*dN/dE

Errors on points are Statistical only

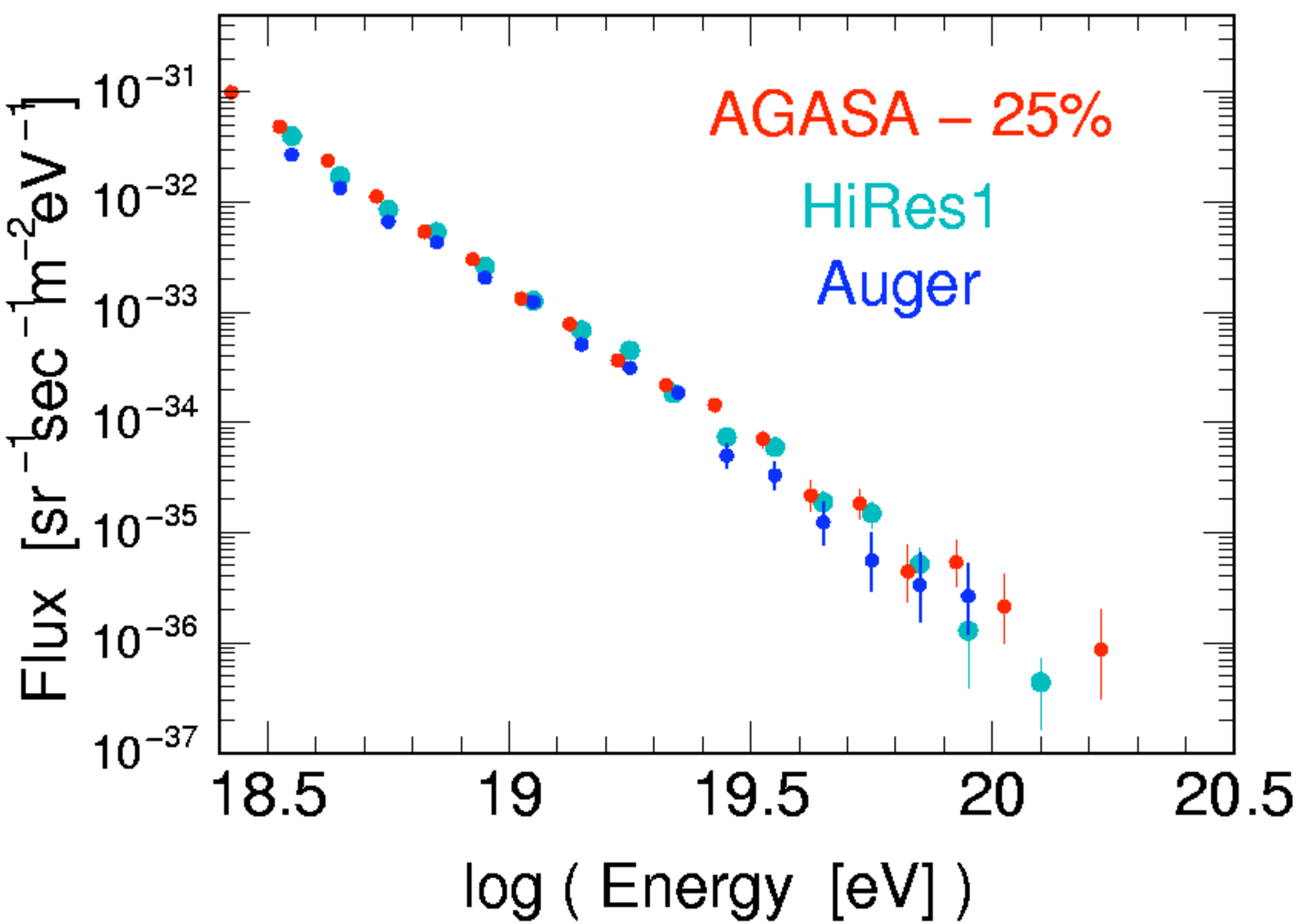
Systematic errors are estimated at two energy regions

- Energy measurement (horizontal)
- Exposure determination (vertical)

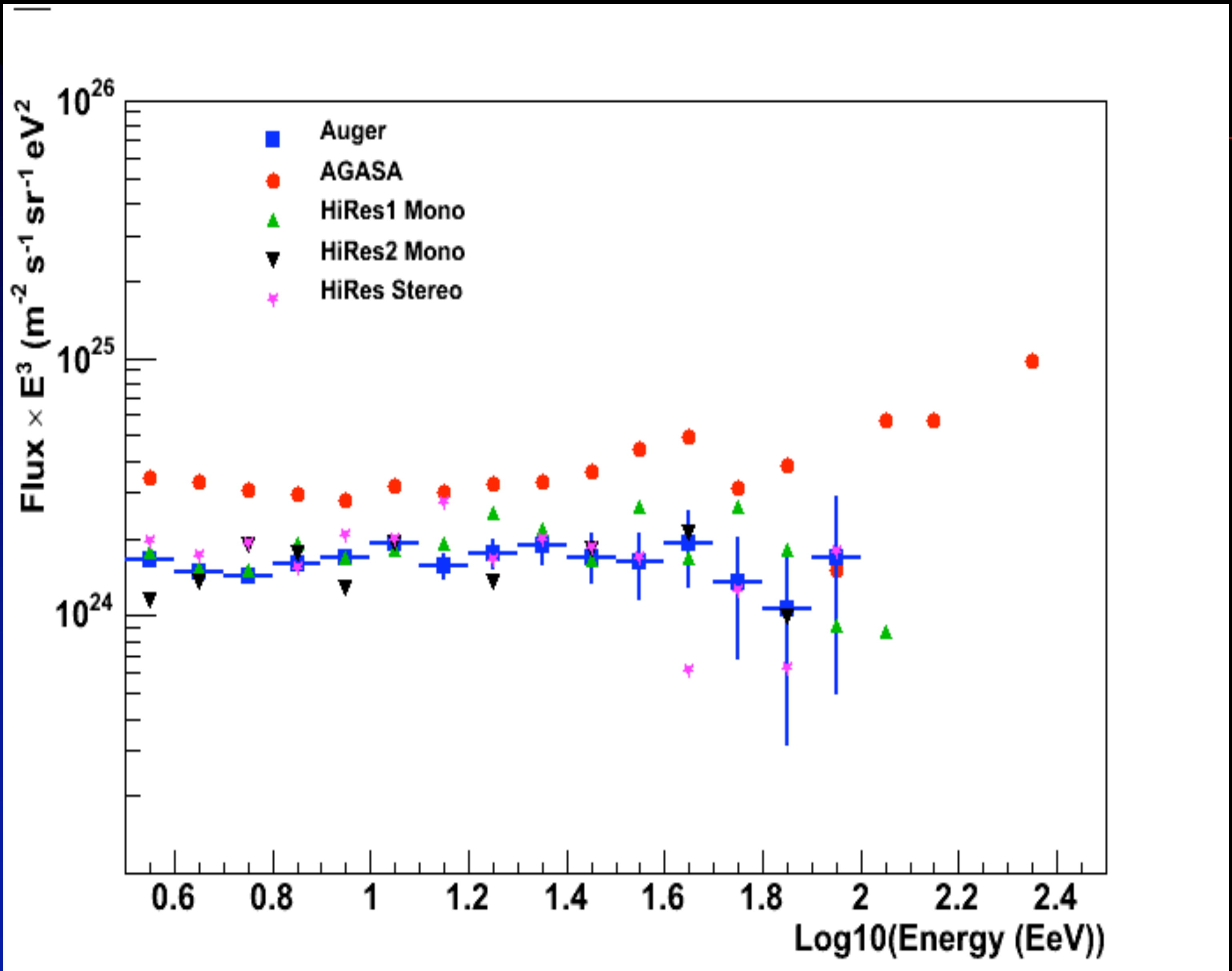
Comparison with HiRes1, AGASA



Comparison with HiRes1, AGASA-25%

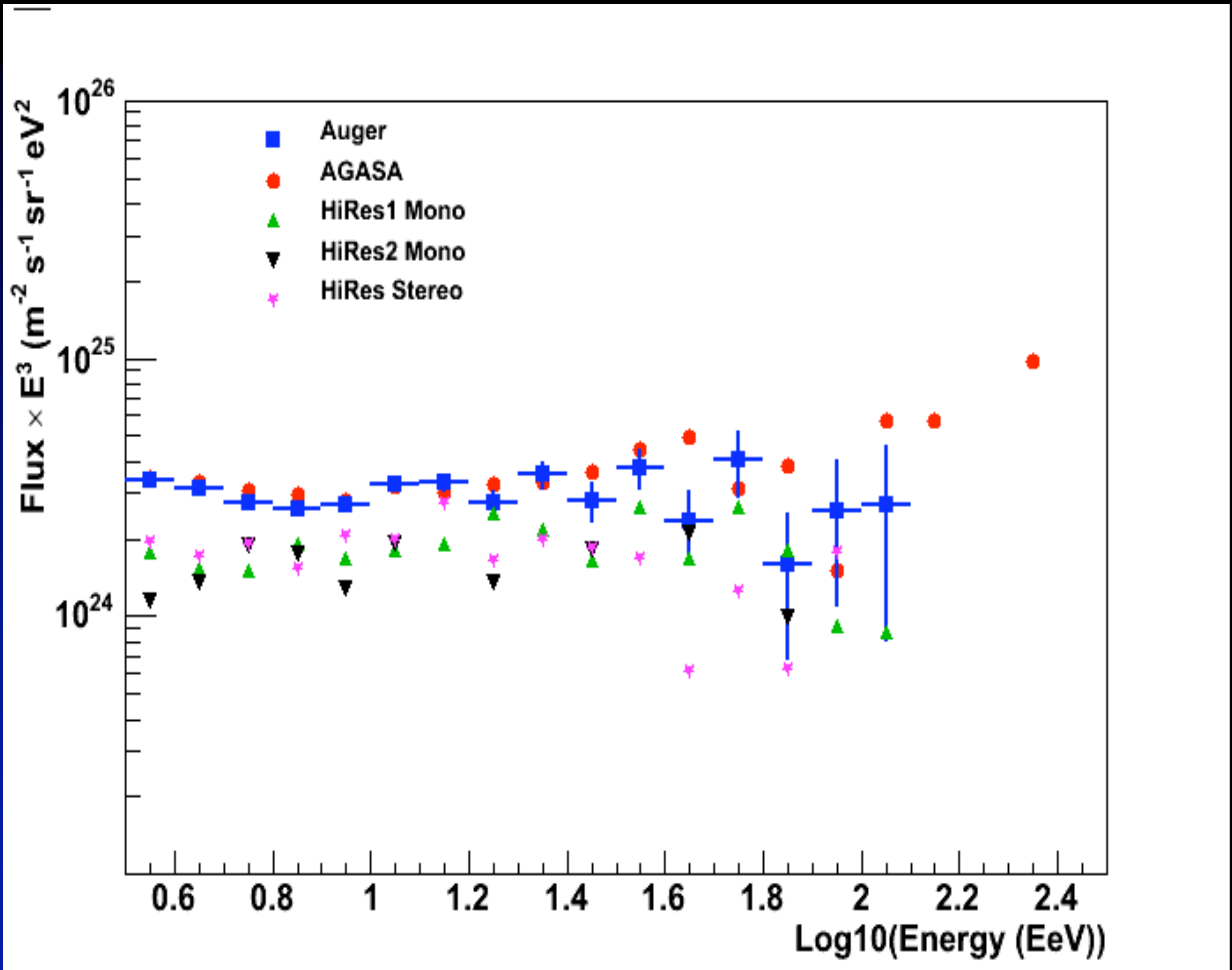


FD + CIC

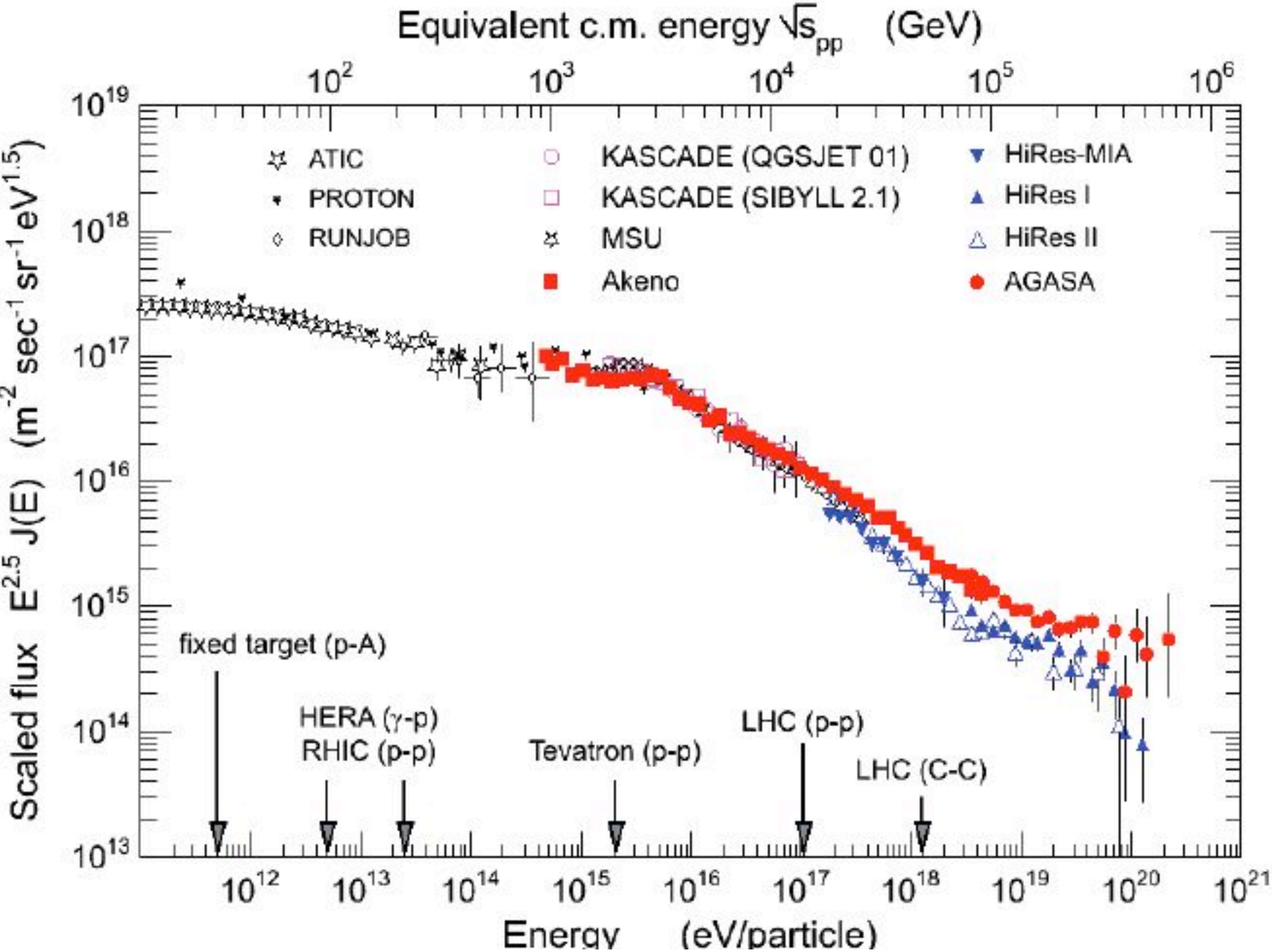


Auger
AGASA
HiRes1 Mono
HiRes2 Mono
HiRes Stereo
10^{26}
10^{25}
10^{24}
Flux × E^3 (m^{-2} s^{-1} sr^{-1} eV^2)
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
Log10(Energy (EeV))

SD + MC


Auger
AGASA
HiRes1 Mono
HiRes2 Mono
HiRes Stereo
Flux × E³ (m⁻² s⁻¹ sr⁻¹ eV²)
10²⁶
10²⁵
10²⁴
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
Log10(Energy (EeV))

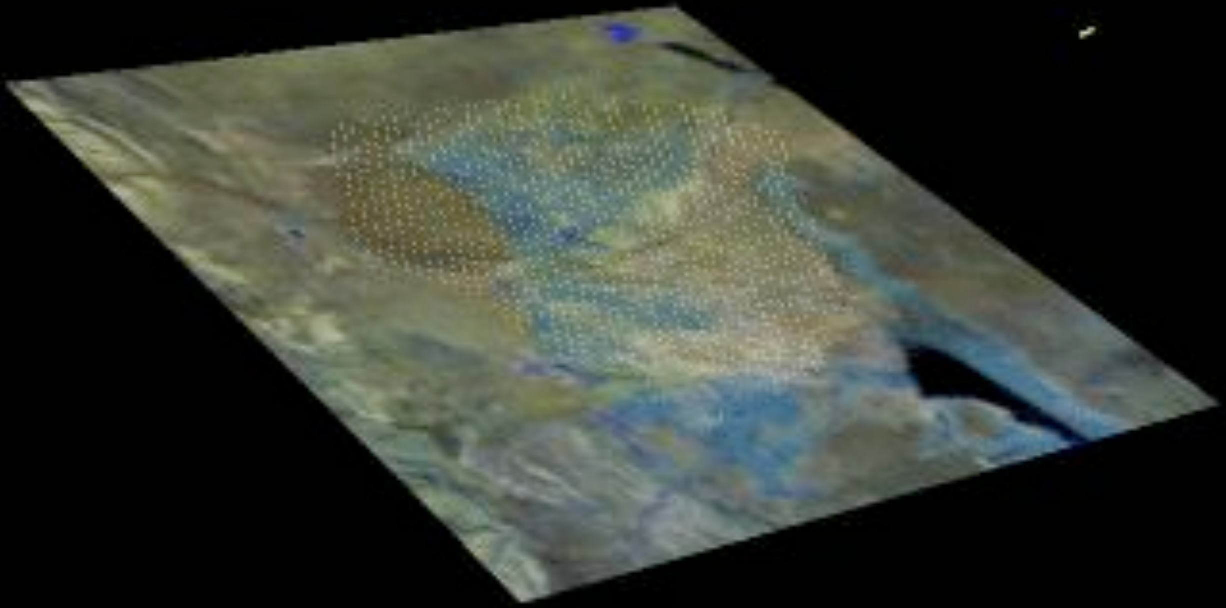
Comparison of energies



Muons on the Side

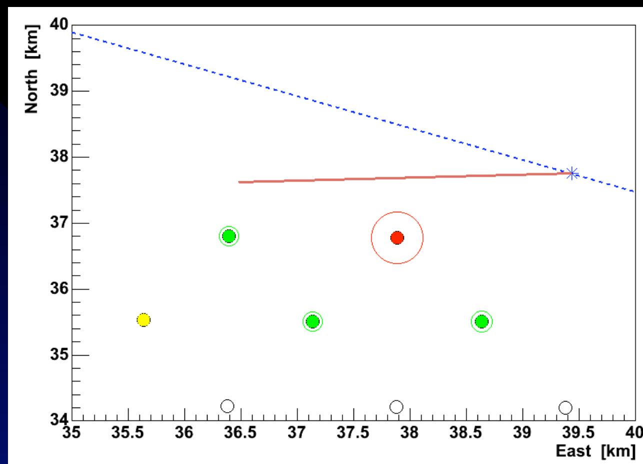
What is the problem?

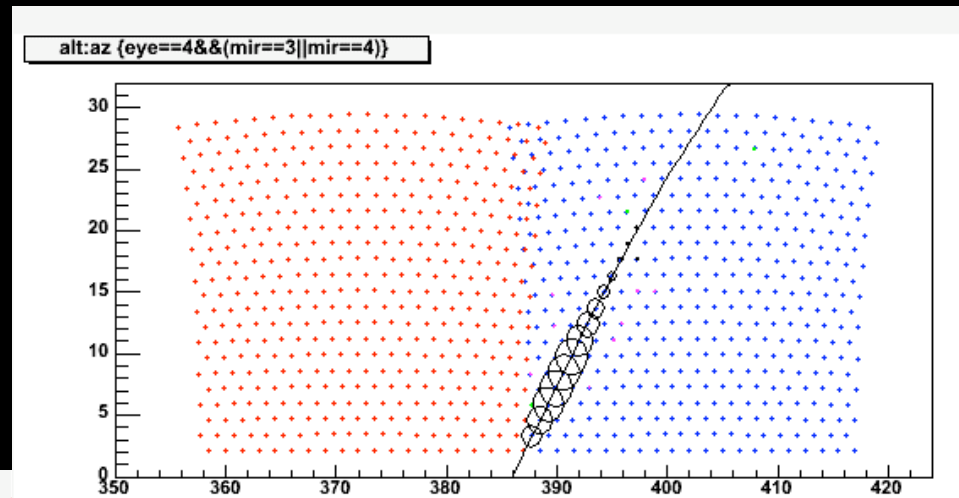
Incorrect Model Detector?
Incorrect Model of Showers?
Heavy Primaries?
New Physics?

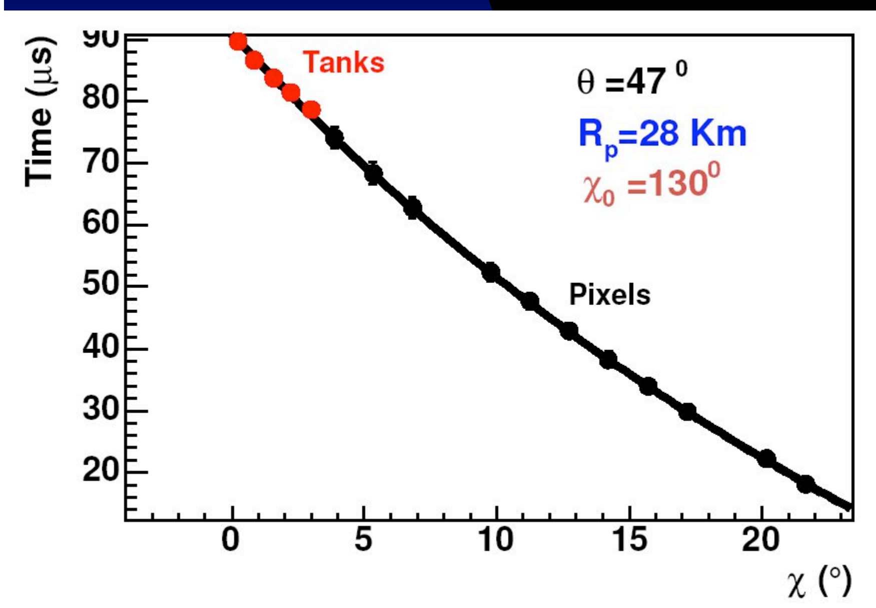


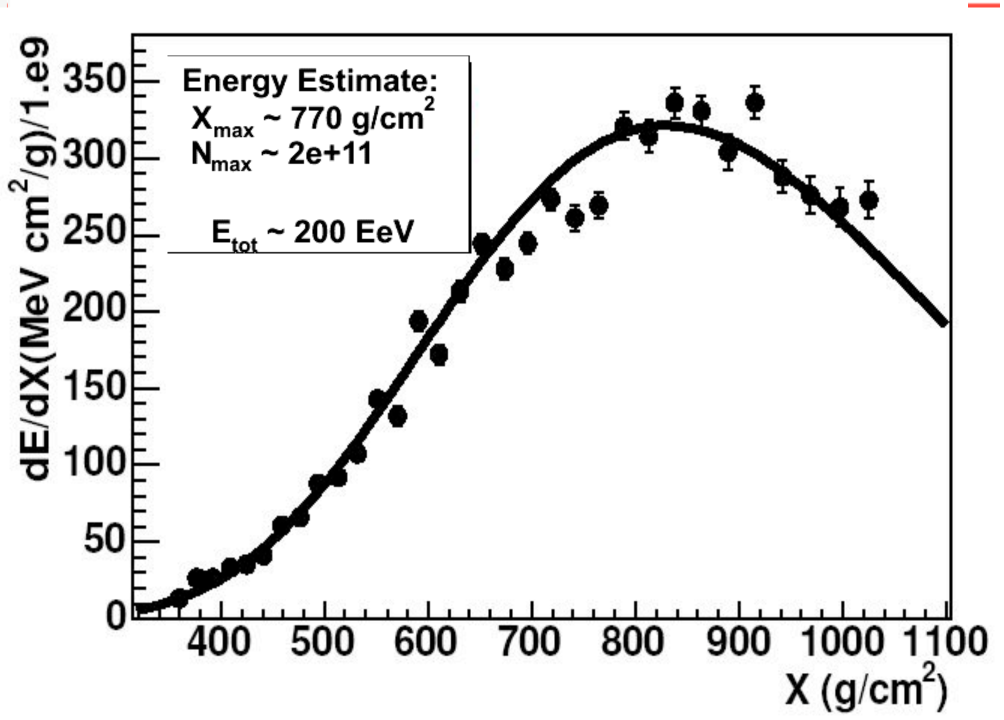
Our Highest Energy Event E_{FD}~2 10^{20}eV

Landed just outside the array, so not used in spectrum!

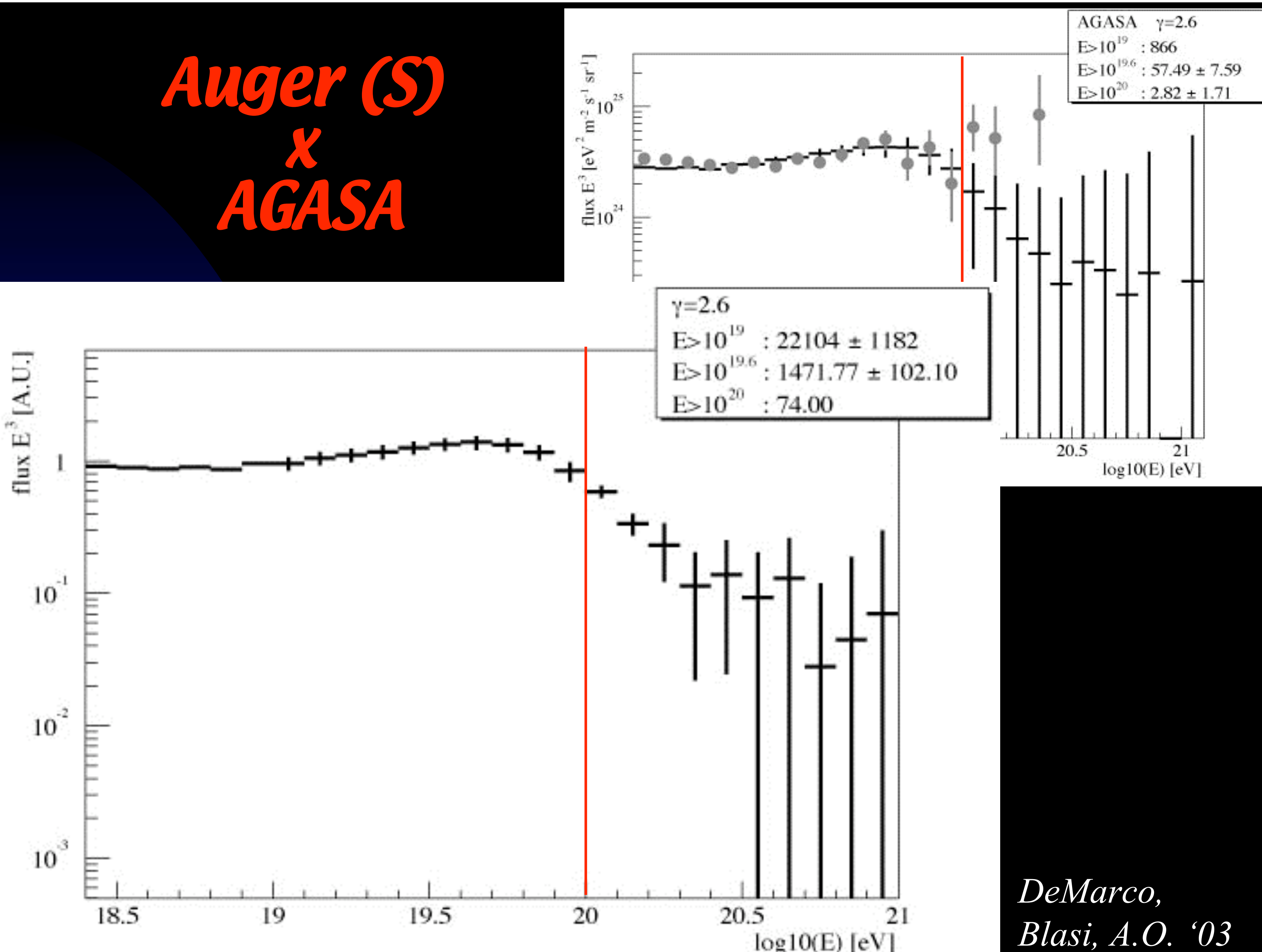








Auger (S) x AGASA



DeMarco, Blasi, A.O. '03

Blind Watchers

TO DO list:

Plausible Sources

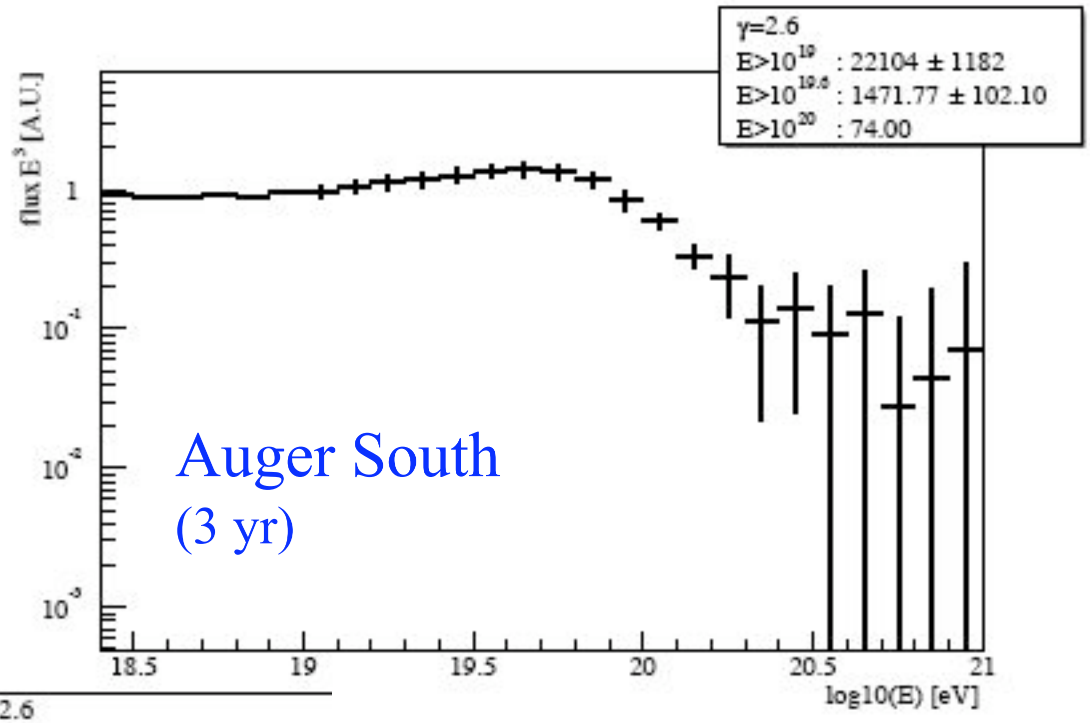
- Shock or ? Acceleration Models
- Spectrum + Composition
- Critical Exposure for Anisotropies

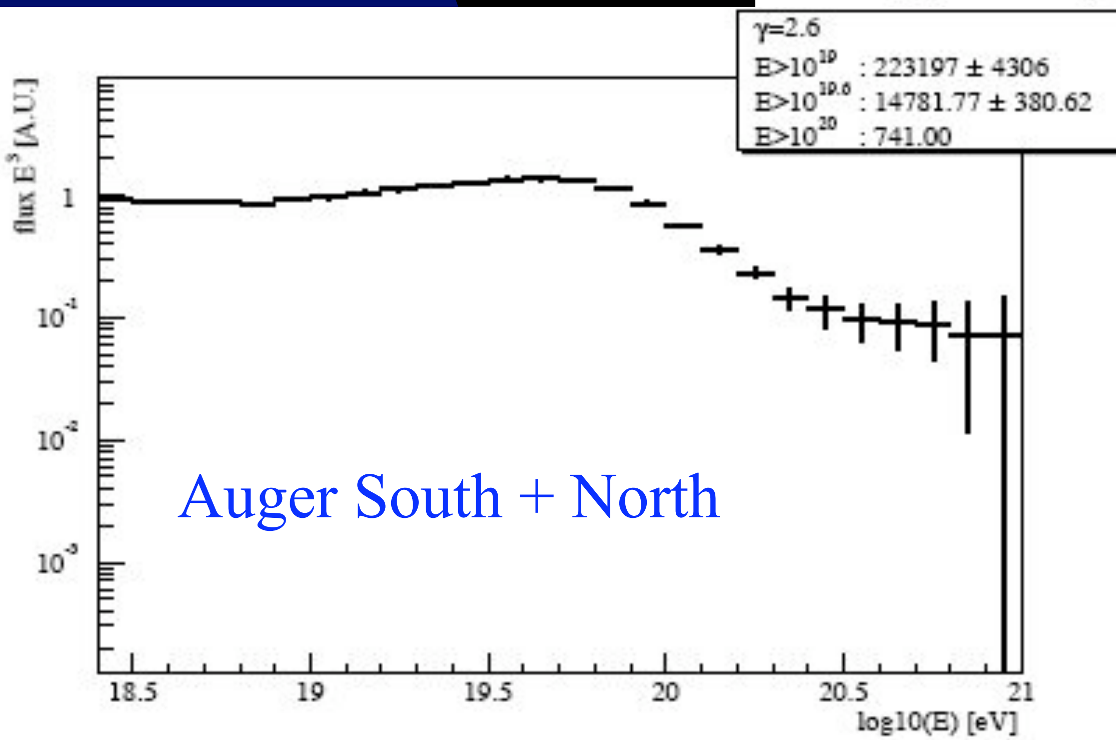
Monte Carlo vs. Fluorescence + CIC - New Physics?

- Fluorescence Yield
- MC Hadronic Models vs. Accelerator Phys (Forward)

Design Pierre Auger North - largest exposure for $$$

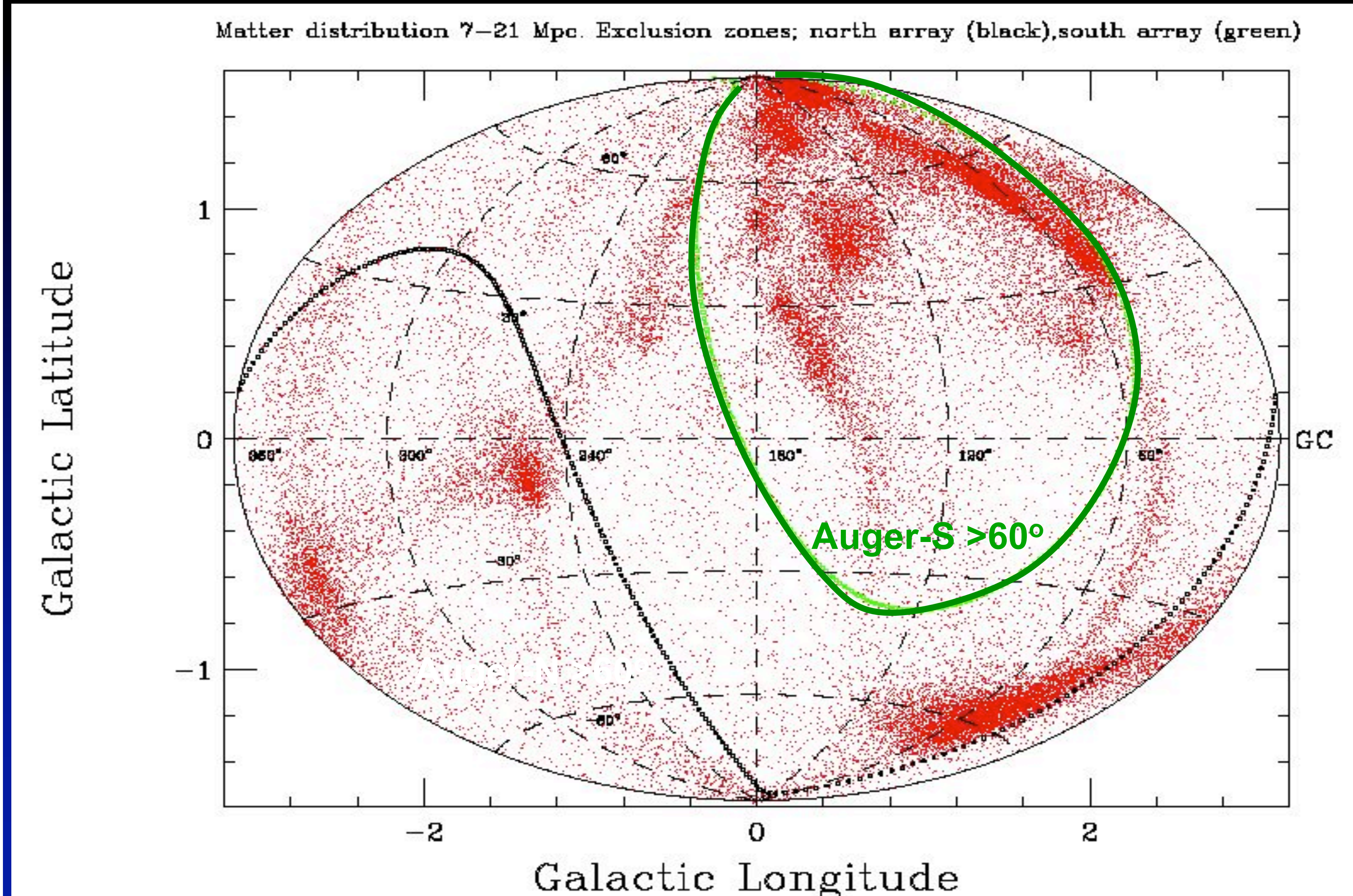
Towards Auger North





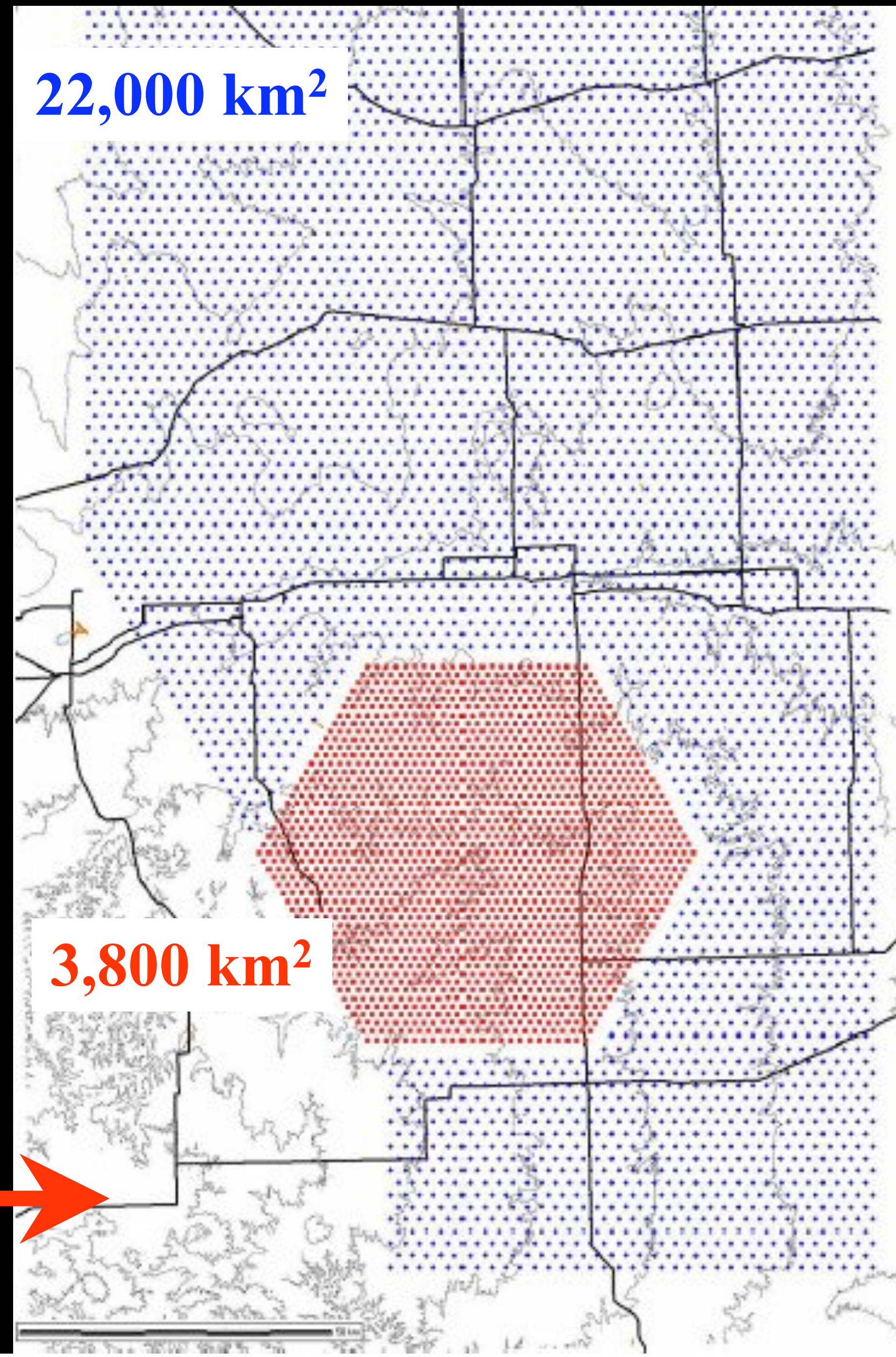
DeMarco, Blasi, AO'03

North ≠ South

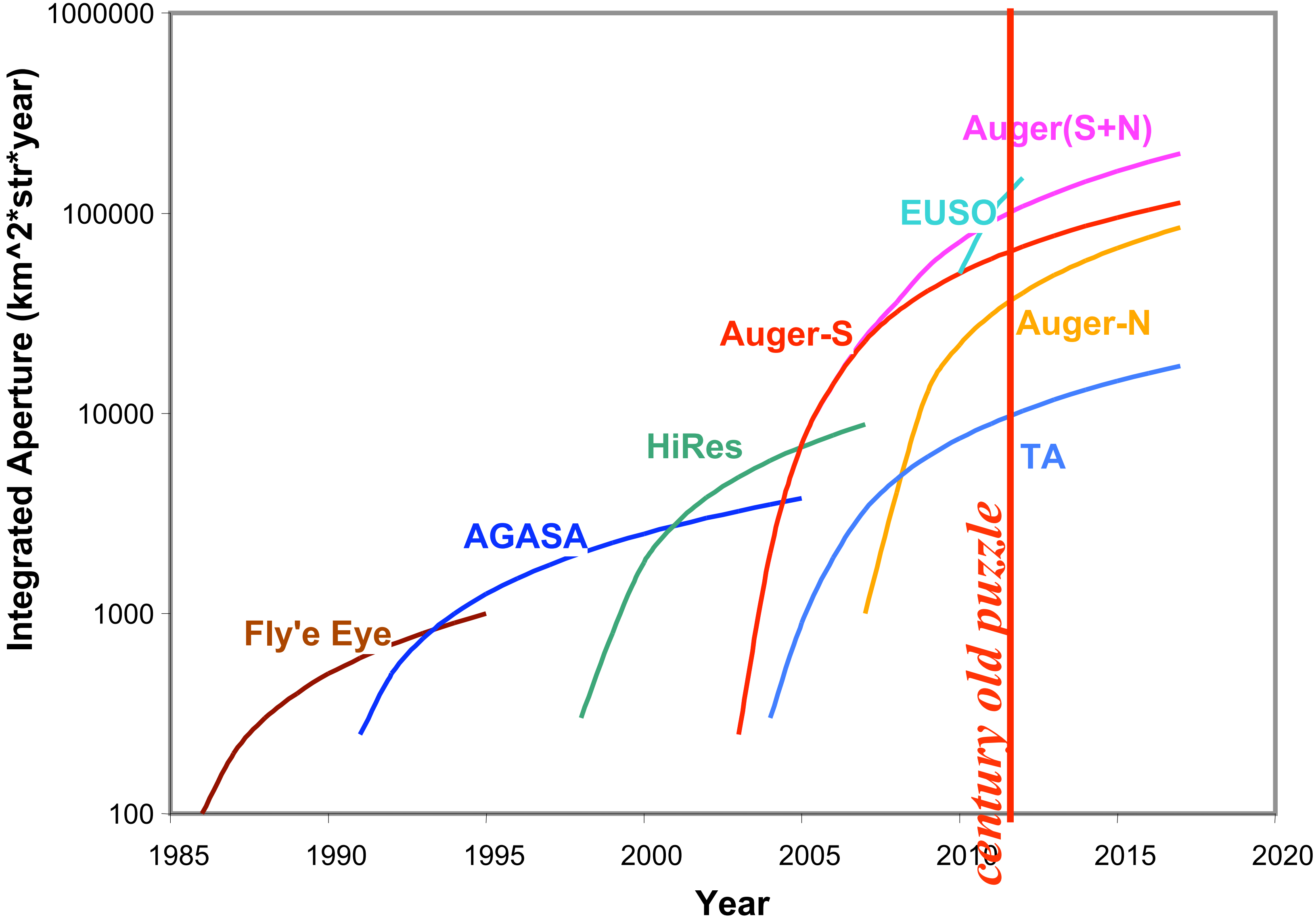


Cronin, astro-ph/0402487

Auger North Colorado site



Integrated Sensitivity of Various Experiments



Cosmic Rays Observables

- ✓ SPECTRUM - great improvement over the next few years (Auger S)
- ✓? COMPOSITION - challenging but doable (Auger S)
- ? ANISOTROPIES in Sky
  - need bigger observatories (Auger S+N)
- MULTIPARTICLE INFO:
  - ✓? TeV gamma rays - yes! Gal CRs
  - ? Neutrinos - yet to come

PIERRE AUGER OBSERVATORY

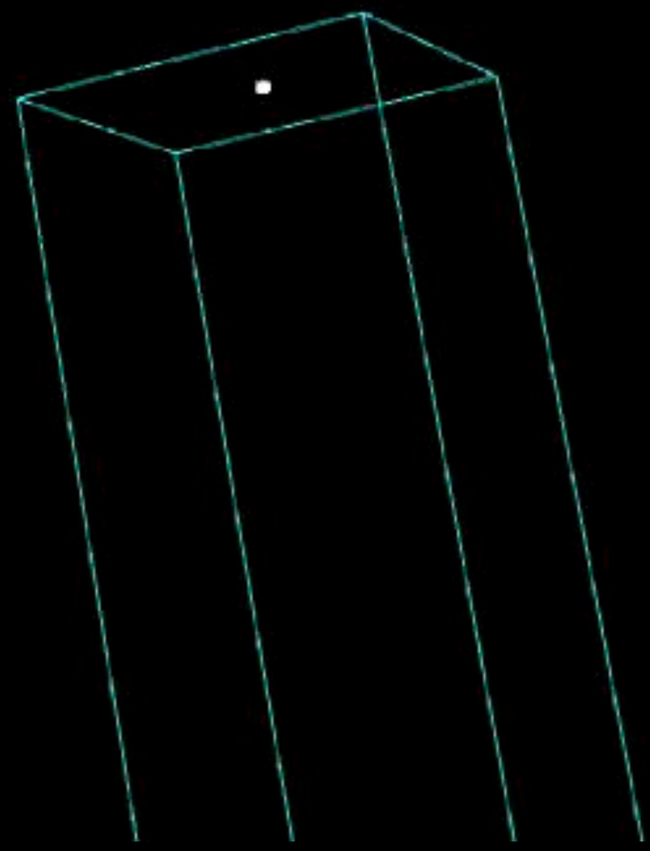
Pierre Auger Project

South & North

to discover
Ultra-High Energy Cosmic Ray
Sources and Begin

Charged Particle Astronomy

Chicago

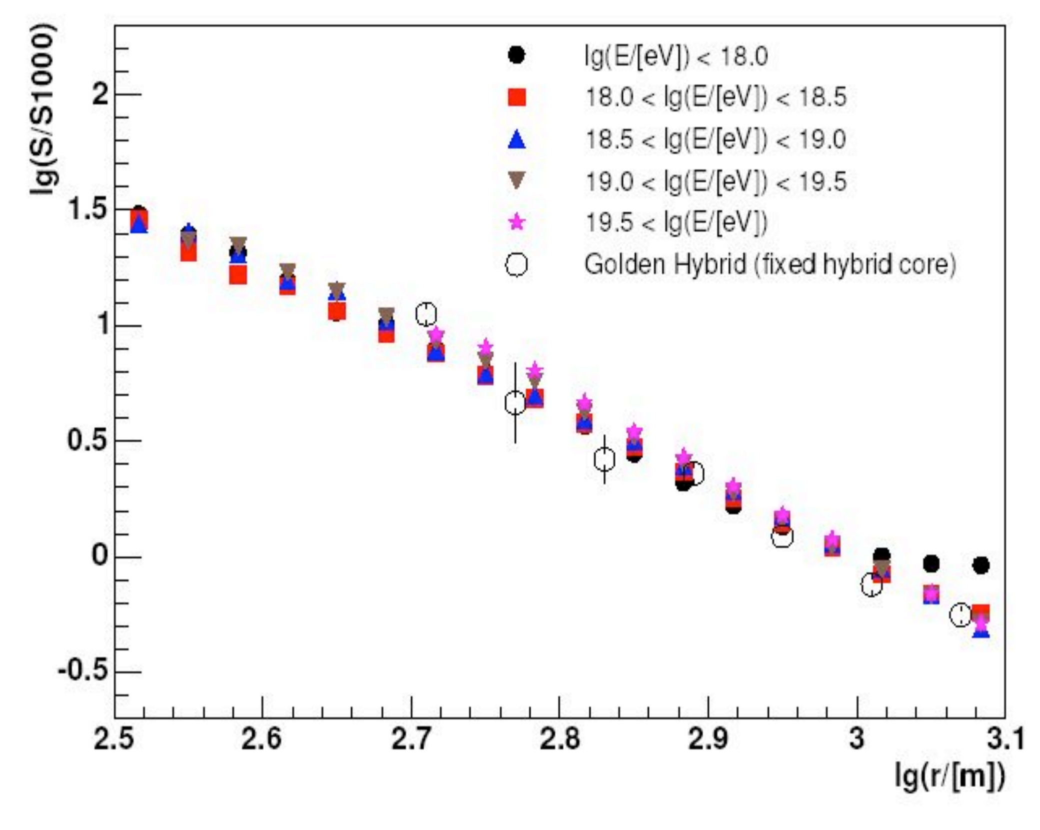


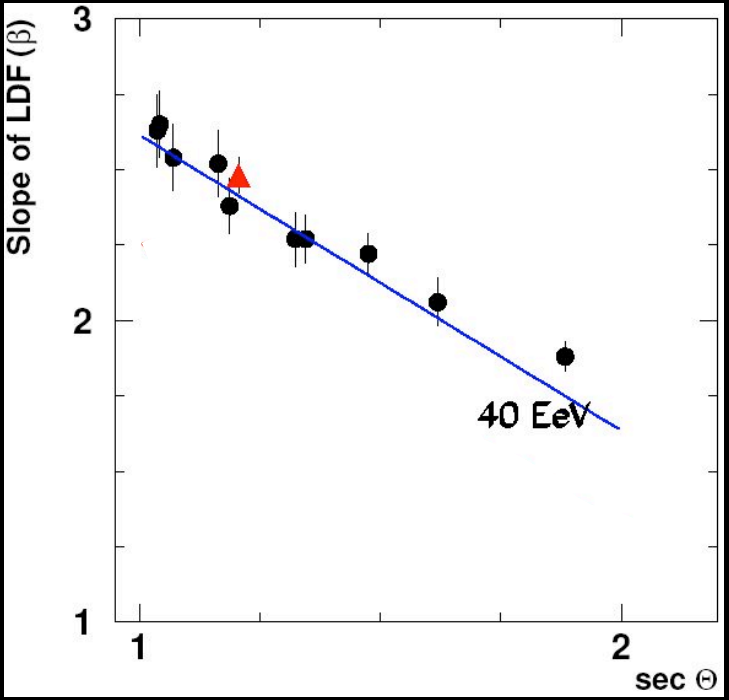
SD fitting function determined from the data

LDF (Lateral Distribution Function):

Distribution of signals versus the core distance r
(transverse distance of detector to the shower axis)

Use a LDF ~ r $^{-\beta}$





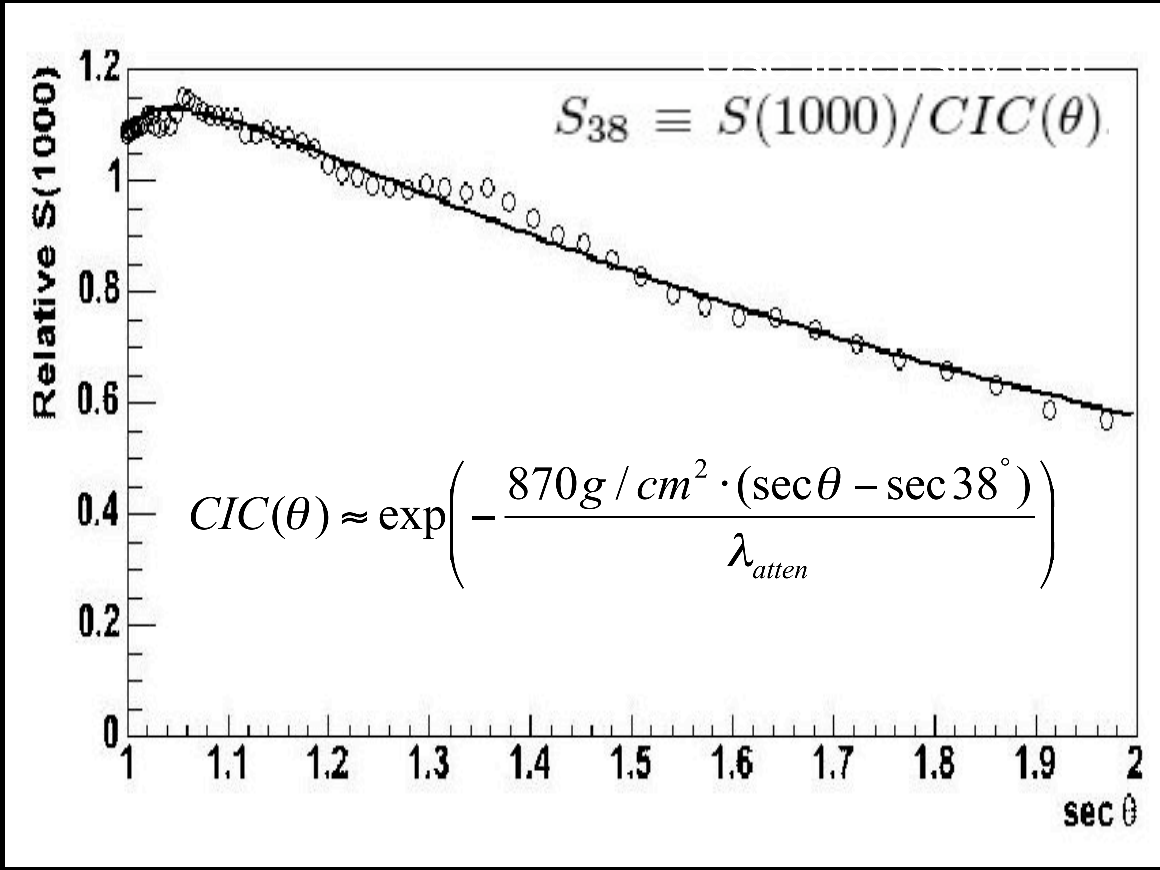
Measured $\beta(E,\theta)$ directly from the data. σ_β ~ 10%

The SD-measured θ dependence (Constant Intensity Cut method)

Shape is scanned in θ using bins of $\Delta\sin^2(\theta)=0.1$

Normalize at the median zenith angle of 38 deg.

Assume CIC(θ) is independent of energy.



Note: bins are correlated!